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SYNTHESIS OF 2,5,6-TRI-*O*-METHYL-D-GLUCOSE[1]

BY C. T. BISHOP AND J. SCHMORAK[2]

ABSTRACT

The previously unknown 2,5,6-tri-*O*-methyl-D-glucose has been prepared from D-glucose. Proof of the constitution of this new sugar derivative is based on its chemical reactions and method of synthesis.

INTRODUCTION

Among the 10 possible isomeric tri-*O*-methyl-D-glucoses the 2,5,6-tri-*O*-methyl derivative has not been reported (1). The synthesis and characterization of this new tri-*O*-methyl ether of D-glucose are described in this report.

The synthesis was accomplished by classical methods of carbohydrate chemistry using non-migratory benzyl and *iso*propylidene groups to block specific hydroxyl groups. D-Glucose was converted to the well-characterized, crystalline, 1,2-*O*-*iso*propylidene-3-*O*-benzyl-5,6-di-*O*-acetyl-D-glucofuranose (I) by a series of reactions previously described (2, 3, 6). Methylation of I by dimethyl sulphate and alkali yielded the 5,6-di-*O*-methyl derivative (II) which was hydrolyzed (III), methanolyzed (IV), and methylated by Purdie's reagents (8) to give methyl-2,5,6-tri-*O*-methyl-3-*O*-benzyl-(α,β)-D-glucofuranoside (V). Removal of the *iso*propylidene group from II was surprisingly difficult requiring hydrolysis with aqueous acid for 10 hr. Two steps were therefore required to obtain IV from II instead of the more usual direct methanolysis of the *iso*propylidene group. The 3-*O*-benzyl group was removed from V by reduction and the methyl glucoside (VI) was hydrolyzed by acid to give the free sugar (VII).

The 2,5,6-tri-*O*-methyl-D-glucose was obtained as a colorless sirup which has not crystallized. The new tri-*O*-methyl-D-glucose has been characterized by conversion to crystalline 2,5,6-tri-*O*-methyl-D-gluconamide.

Proof of constitution of the 2,5,6-tri-*O*-methyl-D-glucose followed from the method of synthesis and was supported by the chemical reactions of the sugar. Salmon and Powell (9) prepared 5,6-di-*O*-methyl-D-glucose by methylation of 1,2-*O*-*iso*propylidene-3-*O*-benzoxymethyl-D-glucose and removal of the blocking groups. The structure of this 5,6-di-*O*-methyl-D-glucose was well established

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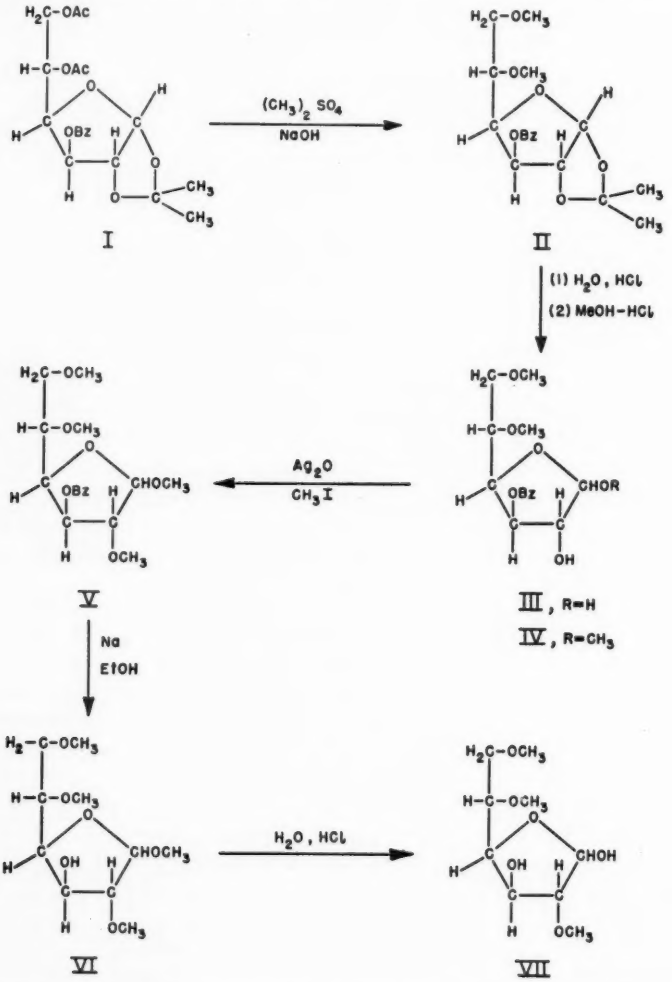
by the identification of di-*O*-methyl glyceraldehyde as a product of periodate oxidation of the sugar. Freudenberg and Plankenhorn (5) prepared the same di-*O*-methyl-D-glucose by methylation of 1,2-*O*-*iso*propylidene-3-*O*-benzyl-5,6-di-*O*-acetyl-D-glucose (I), the starting material used in the present synthesis.



There can be little doubt then that in compound II two methyl ether groups were present in positions 5 and 6. The tri-*O*-methyl-D-glucose (VII) yielded a furanolactone when oxidized by bromine, showing that position 4 was involved in ring formation. After replacement of the 1,2-*O*-*iso*propylidene group by a methyl glycoside (IV) only position 2 was open to methylation. The presence of a methyl ether at position 2 in the final product was confirmed by (*a*) its

failure to give a phenylosazone or *p*-bromophenylosazone, and (*b*) a negative Weerman (10) test given by the derived tri-*O*-methyl-D-gluconamide. It was clear, therefore, that the product of this synthesis could only be 2,5,6-tri-*O*-methyl-D-glucose.

EXPERIMENTAL

Chromatographic separations were carried out in the following solvent systems: (*A*) butanol: ethanol: water—5: 1: 4, (*B*) methyl ethyl ketone: water—2: 1. Sugars were detected on the papers by aniline oxalate spray reagent (7). Evaporations were done under diminished pressure at 40° C. or less. All melting points are corrected and boiling points are bath temperatures. Specific rotations are equilibrium values unless otherwise stated. Yields are calculated on the preceding compound.

*1,2-O-Isopropylidene-3-O-benzyl-5,6-di-O-acetyl-*D*-glucofuranose* (*I*)

This compound was prepared from D-glucose by the following series of reactions, previously described by Freudenberg and his co-workers (2, 3, 6). D-Glucose was condensed with acetone to give 1,2;5,6-di-*O-iso*propylidene-D-glucofuranose which was then benzylated yielding 1,2;5,6-di-*O-iso*propylidene-3-*O*-benzyl-D-glucofuranose. Partial hydrolysis of this compound removed the 5,6-*O-iso*propylidene group, yielding sirupy 1,2-*O-iso*propylidene-3-*O*-benzyl-D-glucofuranose, which was acetylated to give the well-characterized, crystalline 1,2-*O-iso*propylidene-3-*O*-benzyl-5,6-di-*O*-acetyl-D-glucofuranose. This compound had m.p. 119.5–120° C. and $[\alpha]_D^{23} = -52°$ ($c = 2.10$ in tetrachloroethane). Reported (2) values for the same compound are m.p. 119–119.5° C. and $[\alpha]_D = -53°$ (in tetrachloroethane). Analysis: Calc. for $C_{20}H_{26}O_8$: C, 60.88%; H, 6.68%. Found: C, 61.11%; H, 6.75%.

*1,2-O-Isopropylidene-3-O-benzyl-5,6-di-O-methyl-*D*-glucofuranose* (*II*)

Methylation of compound I with dimethyl sulphate and alkali as previously described (5) gave II in 87.6% yield. The product had $[\alpha]_D^{25} = -16°$ ($c = 8.52$ in acetone), in good agreement with the reported (5) value, $[\alpha]_D^{20} = -15.8°$ ($c = 1$ in acetone). Analysis: Calc. for $C_{18}H_{26}O_6(2 \times OCH_3)$: OCH_3, 18.3%. Found OCH_3, 16.8%.

*3-O-Benzyl-5,6-di-O-methyl-*D*-glucofuranose* (*III*)

Compound II (81.4 gm.) was dissolved in ethanol (300 ml.) and 6% aqueous hydrochloric acid (300 ml.) was added. The solution was boiled under reflux for 14 hr., cooled, and neutralized with silver carbonate. Silver salts were filtered and the filtrate was evaporated to a sirup from which water was removed by azeotropic distillation with ethanol. The residual sirup was dried to a constant weight of 65.1 gm. (76.3% yield). The infrared spectrum of this sirup did not contain either of the absorption peaks at 1375 cm.$^{-1}$ or 1170 cm.$^{-1}$ assigned to *iso*propylidene groups. Both of these peaks were present in the infrared spectra of compounds I and II. Infrared analysis was also used to establish the conditions required to remove the *iso*propylidene groups. In preliminary experiments when hydrolyses were stopped at 6, 8, and 10 hr., the products still showed the characteristic *iso*propylidene absorption peaks in

the infrared spectra. Because of the drastic conditions required to remove the *iso*propylidene group, the methyl glucoside (IV) was formed from II in two steps instead of direct methanolysis.

Compound III decomposed during attempted distillation and was not purified to any further extent. Analysis: Calc. for $C_{15}H_{22}O_6$ ($2 \times OCH_3$): OCH_3, 20.8%. Found OCH_3, 22.0%.

Methyl-3-O-benzyl-5,6-di-O-methyl-(α,β)-D-*glucofuranoside* (IV)

Compound III (50.2 gm.) was dissolved in 5% anhydrous methanolic hydrogen chloride (500 ml.) and the solution was allowed to stand till no further reducing power could be detected by aniline oxalate spray reagent. Acid was neutralized by silver carbonate, the silver salts were filtered, and the filtrate was evaporated to a sirup which was dried to constant weight (36.8 gm., 69.9% yield) over phosphorus pentoxide at 0.02 mm. A sample was distilled for analysis; b.p. 145–148° C. at 0.05 mm., $[\alpha]_D^{24} = +12°$ ($c = 3.40$ in ethanol), no mutarotation. Analysis: Calc. for $C_{16}H_{24}O_6$ ($3 \times OCH_3$): C, 61.52%; H, 7.74%; OCH_3, 29.8%. Found: C, 61.72%; H, 7.60%; OCH_3, 28.0%.

Methyl-2,5,6-tri-O-methyl-3-O-benzyl-(α,β)-D-*glucofuranoside* (*V*)

A solution of IV (36.8 gm.) in methyl iodide (300 ml.) was boiled under reflux during the addition of eight 5 gm. portions of silver oxide (8). The additions were made at one-half hour intervals. Silver salts were filtered, washed with acetone, and the filtrate was evaporated to a sirup which was methylated three more times by the same procedure. The sirupy product was dried to constant weight over phosphorus pentoxide at 0.02 mm. (33.5 gm., 87.2% yield). The characteristic absorption band of hydroxyl groups at 3500 $cm.^{-1}$ was barely evident in the infrared spectrum of this product. A sample was distilled for analysis, b.p. 151–156° C. at 0.08 mm., $[\alpha]_D^{20} = +6°$ ($c = 4.03$ in ethanol). Analysis: Calc. for $C_{17}H_{26}O_6$ ($3 \times OCH_3$): C, 62.56%; H, 8.03%; OCH_3, 38.0%. Found: C, 61.98%; H, 7.76%; OCH_3, 37.5%.

Methyl-2,5,6-tri-O-methyl-(α,β)-D-*glucofuranoside* (*VI*)

Compound V (33.5 gm.) was reductively debenzylated by sodium (50 gm.) in ethanol (500 ml.), a method used by Freudenberg and Plankenhorn (4) in their synthesis of 2,4,6-tri-*O*-methyl-D-glucopyranose. Four such debenzylations were required to remove the absorption peak at 1500 $cm.^{-1}$ in the infrared spectrum. This absorption band is characteristic of benzyl groups and was present in the spectrum of V. The debenzylated product was a dark colored sirup (25 gm.) which was distilled, b.p. 130–132° C. at 0.14 mm. giving 16.2 gm. (65.6% yield) of VI, $[\alpha]_D^{20} = -1°$ ($c = 5.1$ in chloroform). Analysis: Calc. for $C_{10}H_{20}O_6$ ($3 \times OCH_3$): C, 50.83%; H, 8.53%; OCH_3, 52.53%. Found: C, 52.11%; H, 8.21%; OCH_3, 47.4%.

This analysis showed that the compound was not pure but contained small amounts of di-*O*-methyl or monomethyl derivative. These compounds could have arisen from incomplete methylation, or more probably, because of the correct analysis of V, from reductive de-etherification during the debenzyl-

ations. Because the reducing sugar, obtained by hydrolysis of this impure glucoside, could be separated very easily by chromatographic methods no further attempt was made to purify VI.

2,5,6-Tri-O-methyl-D-glucofuranose (VII)

The methyl glucoside (VI) was boiled under reflux in 0.5 *N* hydrochloric acid for three and one half hours. The acid was neutralized with silver carbonate, silver salts were filtered, and the filtrate was evaporated to a sirup. Chromatographic examination of this product in solvents A and B revealed the presence of minor components which moved more slowly than the main fraction. The R_G (rate of movement relative to 2,3,4,6-tetra-*O*-methyl-D-glucose) value of the main component was 0.88 in solvent A. From time to time, as samples were required for analysis and derivative formation, portions of the crude tri-*O*-methyl-D-glucose were purified by preparative paper chromatography on Whatman 3MM paper using solvent B. The recovery of pure 2,5,6-tri-*O*-methyl-D-glucofuranose corresponded to 46% yield based on VI or 12.4% based on I. A sample was distilled for analysis, b.p. 155–160° C. at 0.038 mm., $[\alpha]_D^{26} = +11°$ ($c = 4.72$ in water). Analysis: Calc. for $C_9H_{18}O_6$ ($3 \times OCH_3$): C, 48.64%; H, 8.16%; OCH_3, 41.9%. Found: C, 47.95%; H, 7.97%; OCH_3, 41.7%.

Characterization of 2,5,6-Tri-O-methyl-D-glucofuranose

Repeated attempts to form a phenylosazone or *p*-bromophenylosazone from the tri-*O*-methyl-D-glucose were unsuccessful, indicating the presence of a methyl ether at position 2.

A sample (320 mgm.) of the chromatographically pure tri-*O*-methyl-D-glucose (VII) was dissolved in water (3 ml.) and oxidized by bromine (0.75 ml.) in the presence of barium carbonate (150 mgm.) for 18 hr. Hydrochloric acid (12%) was added till the solution was acid and bromine was then removed by aeration. The resulting clear aqueous solution was extracted continuously with chloroform till no more material was removed. The chloroform extract was dried (sodium sulphate) and evaporated to a sirup (292 mgm.). The sirupy acid was lactonized by heating at 0.15 mm. and 100° C. for one hour. The lactone showed the slow mutarotation in water characteristic of furanolactones, $[\alpha]_D^{26} = +67° \rightarrow +62°$ in 71 hr. ($c = 1.13$ in water). Analysis: Calc. for $C_9H_{16}O_6$ ($3 \times OCH_3$): OCH_3, 42.5%. Found OCH_3, 41.7%.

The 2,5,6-tri-*O*-methyl-D-glucono-γ-lactone (250 mgm.) was dissolved in anhydrous methanol and anhydrous ammonia was passed through the solution for one-half hour. The ammoniacal solution was stored at 5° C. for three days and was then evaporated slowly in a desiccator. The amide crystallized as fine needles and was recrystallized from hot ethyl acetate to a constant melting point of 116.5–117° C. (yield, 113.3 mgm.). The 2,5,6-tri-*O*-methyl-D-gluconamide was stable in aqueous solution showing no mutarotation after 48 hr., $[\alpha]_D^{26} = +40°$ ($c = 2.37$ in water), and a Weerman test (10) for α-hydroxy amides was negative. Analysis: Calc. for $C_9H_{19}O_6N$ ($3 \times OCH_3$): C, 45.54%; H, 8.08%; N, 5.91%; OCH_3, 39.2%. Found: C, 45.86%; H, 8.14%; N, 6.05%; OCH_3, 39.1%.

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THE FRIES REARRANGEMENT OF PHENYL ISOBUTYRATE[1]

By T. I. Briggs,[2] G. G. S. Dutton, and E. Merler[3]

ABSTRACT

Phenyl isobutyrate has been found to undergo a normal Fries rearrangement with anhydrous aluminum chloride at 140°C. to give a mixture of 2-hydroxy- (40%) and 4-hydroxy-isobutyrophenone (11%). When the reaction was carried out in nitrobenzene solution at room temperature the 4-isomer was formed in 86% yield. Methylation of these compounds furnished 2- and 4-methoxy-isobutyrophenone, identical with the compounds obtained by direct acylation of anisole. Reduction of the hydroxy-isobutyrophenones, which were also prepared by direct acylation of phenol, afforded an alternative route to the isobutylphenols. The orientation of each methoxy ketone was verified by oxidation to the corresponding acid.

INTRODUCTION

The literature pertaining to the Fries rearrangment has been well documented (3, 4) but these reviews make no mention of the reaction having been applied to esters of phenol in which the acyl group has a branched carbon chain. Since 2-isobutylphenol and 4-isobutylphenol were required as part of a program investigating herbicidal activity of dinitrophenols, their preparation was considered by subjecting phenyl isobutyrate to a Fries rearrangement and reducing the hydroxy ketones thus formed according to the method of Clemmensen (5) as modified by Martin (10).

Examination of the literature revealed very little information on 2-hydroxy- or 2-methoxy-isobutyrophenone, although the corresponding 4-isomers, being readily accessible by direct acylation, have been more fully described. In the course of a series of experiments on the reaction between ferric chloride and phenols, Huber and Brunner (8) found that anhydrous ferric chloride converted phenyl isobutyrate into a mixture of 2- and 4-hydroxy-isobutyrophenone. No yield was quoted for the 2-isomer, which was identified as the oxime, and the 4-isomer was obtained in 16% yield but no derivatives were prepared; the latter was oxidized to 4-hydroxybenzoic acid thus determining the orientation. The work of these authors appears to be the only reference to 2-hydroxy-isobutyrophenone. The results described in the present paper show that when phenyl isobutyrate is reacted with anhydrous aluminum chloride at 140–150°C. for one hour 2-hydroxy-isobutyrophenone is formed in 40% yield and the 4-isomer in 11% yield. These results and the constants of the two isomers agree well with those quoted by Huber and Brunner (8). We have also found that when phenyl isobutyrate is reacted with aluminum chloride in nitrobenzene solution at room temperature 4-hydroxy-isobutyrophenone is formed in 86% yield (1). Both isomers on reduction by Clemmensen's method give the corresponding isobutylphenol, identical with authentic specimens prepared by an alternative route (6).

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The only reference to 2-methoxy-isobutyrophenone is in a paper by Vavon and Décombe (13) in which they report the preparation of this compound by reaction of the Grignard reagent of 2-bromoanisole with isobutyryl chloride. They describe the compound as a solid melting at 96–98°C. but were unable to form an oxime. We have prepared 2-methoxy-isobutyrophenone by two methods. In one case the hydroxy ketone obtained from the Fries rearrangement of phenyl isobutyrate was methylated with dimethyl sulphate and in the other case anisole was acylated directly with isobutyryl chloride. The 2-methoxy-isobutyrophenone, prepared by either route, has so far remained as an oil, but readily formed a crystalline 2,4-dinitrophenylhydrazone and a crystalline oxime. Portions of the 2- and 4-methoxy-isobutyrophenones were oxidized with alkaline permanganate to 2-methoxybenzoic and anisic acids, thus confirming the orientation of the substituents. In view of recent work (7) on the anomalous reactivity of 2-methoxyphenylmagnesium halides there must be some doubt whether the compound isolated by Vavon and Décombe was 2-methoxy-isobutyrophenone, owing to the lack of supporting evidence.

EXPERIMENTAL*

Phenyl Isobutyrate

Isobutyryl chloride (106 gm., 1.0 mole), prepared from redistilled thionyl chloride and isobutyric acid in 95% yield by a standard procedure (9), was gradually added at room temperature to phenol (104 gm., 1.1 moles) when hydrogen chloride was vigorously evolved. The crude ester, obtained by distillation, was cooled to 0°C., repeatedly washed with ice-cold potassium hydroxide solution (1 *N*), and dried over solid potassium hydroxide, the flask being constantly immersed in an ice bath. Fractionation gave phenyl isobutyrate (161 gm., 81%) as a clear liquid boiling at 211°C. and having n^{25}, 1.4919. Literature (2), 112°C. (25.5 mm.).

High Temperature Fries Rearrangement of Phenyl Isobutyrate

Anhydrous aluminum chloride (21.5 gm., 0.16 mole) was placed in a 500 ml. flask and heated to 70°C. Phenyl isobutyrate (20 gm., 0.10 mole) was added in small portions over a period of 10 to 15 min. with stirring. A vigorous evolution of hydrogen chloride occurred and the temperature rose to about 100°C. When the addition of ester was complete the temperature was rapidly raised to 140–150°C. and maintained between these limits for one hour. The reaction mixture was cooled to room temperature and the glassy solid decomposed by the addition of hydrochloric acid (100 ml., 6 *N*). After the solution was heated for five minutes on the steam cone in order to complete the hydrolysis, the viscous red oil was separated and washed with warm hydrochloric acid (30 ml., 6 *N*) and two portions of warm water. Distillation of the oil *in vacuo* yielded two fractions which were separately redistilled.

Fraction 1, identified as 2-hydroxy-isobutyrophenone, distilled as a clear liquid (8.0 gm., 40%) boiling at 68°C. (0.4 mm.) and having n^{25}, 1.5367. Literature (8) 110°C. (10 mm.). *2,4-Dinitrophenylhydrazone*, m.p. 186°C.

**All melting and boiling points are uncorrected.*

(decomp.). Anal. calc. for $C_{16}H_{16}O_5N_4$: N, 16.2%. Found: N, 16.3%. *Semicarbazone*, m.p. 178°C. Anal. calc. for $C_{11}H_{15}O_2N_3$: N, 19.0%. Found: N, 19.1%. *Oxime*, m.p. 126°C.; literature (8), m.p. 129°C. Anal. calc. for $C_{10}H_{13}O_2N$: N, 7.8%. Found: N, 7.9%.

Fraction 2, identified as 4-hydroxy-isobutyrophenone, distilled as an oil (2.2 gm., 11%) boiling at 128°C. (0.1 mm.). On standing the oil solidified and recrystallization from ether – petroleum ether gave the pure compound m.p. 54°C. Literature (8), m.p. 56°C. *2,4-Dinitrophenylhydrazone*, m.p. 166°C. (decomp.). Anal. calc. for $C_{16}H_{16}O_5N_4$: N, 16.2%. Found: N, 16.2%. *Semicarbazone*, m.p. 199°C. Anal. calc. for $C_{11}H_{15}O_2N_3$: N, 19.0%. Found: N, 19.1%. *Oxime*, m.p. 159°C. Anal. calc. for $C_{10}H_{13}O_2N$: N, 7.8%. Found: N, 7.7%.

Low Temperature Fries Rearrangement of Phenyl Isobutyrate

Phenyl isobutyrate (11 gm., 0.07 mole) was added in small portions at room temperature to a solution of anhydrous aluminum chloride (11 gm., 0.09 mole) in nitrobenzene (50 ml.). The reaction was allowed to proceed at 25°C. for 40 hr. and then the solution was poured on to ice and hydrochloric acid. When hydrolysis was complete the mixture was extracted with ether and the ethereal solution extracted with potassium hydroxide solution (1 *N*). The alkaline solution was acidified and re-extracted with ether. Removal of the solvent and distillation *in vacuo* yielded 4-hydroxy-isobutyrophenone (9.5 gm., 86%) boiling at 133°C. (0.5 mm.) and m.p. 54°C. on recrystallization from ether – petroleum ether (1).

The following crystalline derivatives were found not to depress the melting point of the same derivatives obtained from fraction 2 obtained in the high temperature rearrangement: 2,4-dinitrophenylhydrazone, m.p. 166°C. (decomp.); oxime, m.p. 159°C.; semicarbazone, m.p. 199°C.

Acylation of Phenol with Isobutyryl Chloride

Anhydrous aluminum chloride (13.3 gm., 0.1 mole) and a solution of phenol (4.7 gm., 0.05 mole) in nitrobenzene (50 ml.) were placed in a flask fitted with a mechanical stirrer and a reflux condenser. Isobutyryl chloride (5.3 gm., 0.05 mole) was gradually added with vigorous stirring and the solution heated on the steam cone for one half-hour with continuous stirring. The cooled solution was poured on to cracked ice and hydrochloric acid. Distillation of the resulting oil yielded two fractions which were separately redistilled.

Fraction 1 was identified as 2-hydroxy-isobutyrophenone (0.5 gm., 7%) which distilled as an oil boiling at 67°C. (0.7 mm.) and having n^{25}, 1.5355. 2,4-Dinitrophenylhydrazone m.p. 186°C. (decomp.).

Fraction 2 was identified as 4-hydroxy-isobutyrophenone (6 gm., 73%), which distilled at 135°C. (0.7 mm.) and on recrystallization melted at 54°C. 2,4-Dinitrophenylhydrazone m.p. 166°C. (decomp.).

2- and 4-Methoxy-isobutyrophenone

Dimethyl sulphate (3.2 gm.) was added to a solution of 2-hydroxy-isobutyrophenone (2.5 gm.) in water (50 ml.) containing potassium hydroxide (1.2 gm.). The solution was warmed to 50°C. and stirred for six hours. The oil which

separated was extracted with ether and the ethereal solution was washed with aqueous alkali and with water. Removal of the ether and distillation yielded *2-methoxy-isobutyrophenone* (2.2 gm., 90%) boiling at 71°C. (0.3 mm.) and n^{25}, 1.5229. The oil showed no tendency to crystallize. Literature (13), m.p. 97–98°C. *2,4-Dinitrophenylhydrazone*, m.p. 136°C. Anal. calc. for $C_{17}H_{18}O_5N_4$: N, 15.6%. Found: N, 15.7%. *Oxime*, m.p. 105°C. Anal. calc. for $C_{11}H_{15}O_2N$: N, 7.2%. Found: N, 7.2%.

4-Methoxy-isobutyrophenone, prepared in a similar way, was obtained in 90% yield as an oil, b.p. 89°C. (0.3 mm.) and n^{25}, 1.5340. Literature, b.p. 82.7°C. (0.01 mm.) (11), n^{20}, 1.5363 (12). *2,4-Dinitrophenylhydrazone*, m.p. 117°C. Anal. calc. for $C_{17}H_{18}O_5N_4$: N, 15.6%. Found: N, 15.6%. Semicarbazone, m.p. 181°C. Literature (11), m.p. 183–184°C. Anal. calc. for $C_{12}H_{17}O_2N_3$: N, 17.9%. Found: N, 17.9%. *Oxime*, m.p. 86°C. Literature (12) quotes the oxime as an oil. Anal. calc. for $C_{11}H_{15}O_2N$: N, 7.2%. Found: N, 7.2%.

Preparation of 2-Methoxybenzoic Acid and Anisic Acid

2-Methoxy-isobutyrophenone (2.0 gm., 0.01 mole) was added to a solution of anhydrous sodium carbonate (1.5 gm., 0.014 mole) and potassium permanganate (3.2 gm., 0.02 mole) in water (60 ml.) and the solution refluxed until oily drops were no longer observed in the condenser (about four hours). The cooled solution was filtered from precipitated manganese dioxide, the filtrate acidified with hydrochloric acid and extracted with ether. The ethereal solution was washed with water, dried with magnesium sulphate, and evaporated. The resulting solid, recrystallized from carbon tetrachloride, had m.p. 100°C. alone or when mixed with an authentic sample of 2-methoxybenzoic acid.

4-Methoxy-isobutyrophenone was oxidized in a similar manner and the acid obtained, recrystallized from water, had m.p. 184°C. alone or when mixed with an authentic sample of anisic acid.

Acylation of Anisole with Isobutyryl Chloride

Isobutyryl chloride (20 gm., 0.18 mole) was added with stirring over one half-hour to a mixture of anhydrous aluminum chloride (33 gm., 0.25 mole) and anisole (21 gm., 0.18 mole) in carbon disulphide (200 ml.). The solution was refluxed for one hour with stirring. The cooled reaction mixture was poured onto ice and hydrochloric acid and the aqueous layer extracted with ether. The oil resulting from the evaporation of the combined solvent extractions yielded two fractions on distillation and each was separately redistilled.

Fraction 1 gave 2-methoxy-isobutyrophenone (1 gm., 3%) as a liquid boiling at 75°C. (0.3 mm.) and having n^{25}, 1.5229. 2,4-Dinitrophenylhydrazone, m.p. 135°C.

Fraction 2 gave 4-methoxy-isobutyrophenone (19 gm., 60%) as a liquid boiling at 89°C. (0.3 mm.) and having n^{25}, 1.5341. 2,4-Dinitrophenylhydrazone, m.p. 115°C.

2-Isobutylphenol

2-Hydroxy-isobutyrophenone (2 gm.) was refluxed with a mixture of zinc amalgam (5 gm.), concentrated hydrochloric acid (8 ml.), and glacial acetic

acid (8 ml.) until a negative test was obtained with 2,4-dinitrophenylhydrazine (about seven hours). 2-Isobutylphenol was obtained in 55% yield as an oil boiling at 62°C. (0.7 mm.). 3,5-Dinitrobenzoate m.p. and mixed m.p. 83°C. (6).

4-Isobutylphenol

4-Hydroxy-isobutyrophenone (2 gm.) was reduced as above and 4-isobutylphenol was obtained in 83% yield as an oil boiling at 82°C. (0.7 mm.). The oil solidified on standing and recrystallization gave the pure phenol m.p. and mixed m.p. 52°C. (1).

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POLYMER-ANALOGOUS DENITRATION OF POLYSACCHARIDE NITRATES: A STUDY OF SOME REDUCTIVE METHODS WITH MODEL COMPOUNDS AND CELLULOSE NITRATE[1]

By E. P. Swan[2] and L. D. Hayward

ABSTRACT

Crystalline D-mannitol penta- and hexa-nitrates, methyl-β-D-glucopyranoside tetranitrate, and maltose and cellobiose octanitrates were prepared as model substances of known constitution for study of denitration reactions possibly applicable to polysaccharide nitrates. Heterogeneous catalytic hydrogenation smoothly regenerated the parent carbohydrates from the model compounds in nearly quantitative yield and removed 0.42 and 0.63 nitrate groups per glucose unit from cellulose nitrates of 13.3 and 10.7% N respectively. Raney nickel was conveniently removed from the hydrogenated cellulose nitrates by means of a magnet. The action of methyl magnesium iodide, lithium aluminum hydride, or low-pressure hydrogenation with a homogeneous cupric acetate catalyst caused less complete denitration of the mannitol or cellobiose polynitrates. The nitration–fractionation–denitration sequence as a means of isolation of undegraded polysaccharides from natural sources is discussed.

INTRODUCTION

Nitration alone of all polysaccharide substitution reactions has been proved to be polymer-analogous* when carefully controlled (37, 23, 24, 25, 32). Nitration of plant tissue followed by fractionation (14, 25) with organic solvents has permitted separation of the nitrated polysaccharide components which, in the most careful work, were probably closely polymer-analogous to the "native" macromolecules (31); the physical properties of polysaccharide nitrate solutions thus obtained have been extensively studied, particularly for the commercial evaluation of cellulosic fibers of plant origin (8, 25).

So far the use of polysaccharide nitrate derivatives for chemical characterization of chain units and the sequence and branching patterns of the macromolecules has been limited by the lack of a method of quantitative and polymer-analogous denitration (5, 23, 28, 35). Such a method would complete the cycle of operations through which pure polysaccharides could be isolated from natural sources with minimum chemical alteration and in a form suitable for structural studies by conventional methylation, hydrolysis, and chromatography techniques.

The ease of quantitative removal of nitric acid ester groups with regeneration of the alcohol from alkyl and sugar nitrates by reported methods suggested that further study of these with certain hexitol, monosaccharide, and disaccharide polynitrates as model substances might lead to a method applicable to the nitrated polysaccharides. The model substances (Table I) were selected (*a*) to

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**We propose to define a polymer-analogous reaction as a chemical transformation of an organic polymer in which the carbon skeleton of the chains and units and the links between units remain unaltered.*

TABLE I

THE CARBOHYDRATE POLYNITRATE MODEL COMPOUNDS

Carbohydrate nitrate	Constants found				Reported constants				
	M.p.,°C.*	$[\alpha]_D^{20}$	c	Solvent	M.p.,°C.	$[\alpha]_D^{20}$	c	Solvent	Ref.
Cellobiose octanitrate	150	+88.92	5	Acetone	154 140	+22.18	6	Acetone	(2) (6)
Maltose octanitrate	164–165	+8.53	1	Dioxane	164–165 164–165	+128.6	35	Gl. HOAc	(2) (36)
D-Mannitol hexanitrate	111	+43.03	2	Ethanol	111–112	+43.1	2	Ethanol	(15)
D-Mannitol-1,2,3,5,6-pentanitrate	80	+47.16	4	Ethanol	81–82	+47.7	4.4	Ethanol	(7)
Methyl-β-D-glucopyranoside tetranitrate	115–116	+11.62	4	$CHCl_3$	116.5	+11.6	4	$CHCl_3$	(6)

**All melting points were corrected.*

contain atomic linkages characteristic of polysaccharides, (*b*) to yield on denitration easily identifiable parent compounds, and (*c*) to be preparable in crystalline form by direct nitration of the available parent substances. Their identity was established from the physical constants (Table I) and nitrogen analyses (Table IV) and by nearly quantitative denitration to the parent compounds (Table II).

Catalytic hydrogenation (15, 16, 19, 20, 21), hydrolysis of Grignard adducts (17), and reduction with lithium aluminum hydride (30) appeared to be the most promising methods of denitration and were selected for trial, while alkaline and acid hydrolyses and the solvolyses of nitric acid esters (1, 3, 4, 11, 12, 18, 22, 25) were rejected as unsuitable for polysaccharide structure studies.

The results obtained from the application of Kuhn's catalytic hydrogenation method (15, 19, 21) to the model carbohydrate nitrates are summarized in Table II. The yield of reasonably pure parent substance was excellent in each

TABLE II

PRODUCTS FROM HYDROGENOLYSIS OF THE MODEL COMPOUNDS*

Parent carbohydrate	Number of nitrate groups	Yield, %	M.p.,°C.†	Mixed m.p.,°C.†	Reported m.p.,°C.
β-Cellobiose	8	99.2	242	241	225 (26); 230 (34)
β-Maltose.H_2O	8	99.5	98–100	98–100	102–103 (26)
D-Mannitol	6	97.5	161–164	161–163	166 (26)
D-Mannitol	5	99.9	166–167	166–167	166 (26)
Methyl-β-D-glucopyranoside.$1/2H_2O$	4	99.5	104–107	104–106	104–106 (27)

**In ethanol at 25°C., hydrogen pressure 30–57 p.s.i., palladium–charcoal catalyst, 0.3 to 0.5 gm. per gram of nitrate.*

†All melting points were corrected.

case and the identity of the product was established by a mixed melting point with an authentic specimen.

Hepworth (17) in 1921 reported that alkyl nitrates were denitrated by the action of methyl or ethyl magnesium halides followed by dilute acid hydrolysis of the Grignard adduct; the only product which had been isolated however was N,N-dimethyl (or ethyl) hydroxylamine. When applied by us to D-mannitol hexanitrate and cellobiose octanitrate this procedure gave 34 and 11% yields respectively of the corresponding polyols isolated as the fully acetylated derivatives. To avoid degradation the Grignard addition complex was broken up with dilute acetic acid, and concentration and acetylation of the residue were necessary to separate the water soluble polyols from the inorganic salts.

Reduction of D-mannitol hexanitrate by an ethereal solution of lithium aluminum hydride (30) gave an 87% yield of D-mannitol isolated as the corresponding hexaacetate. The adverse side reactions anticipated from the formation of ammonia and nitrous oxide, the degradative action reported by Soffer *et al.*, and the necessary acetylation step weighed against the general usefulness of this reaction as a denitration technique for the more sensitive sugar and polysaccharide polynitrates.

Two problems were encountered in applying the catalytic hydrogenation method to cellulose nitrate: (*a*) the reaction stopped when the partially denitrated product became sufficiently insoluble in the hydrogenation solvent to form a fourth phase, and (*b*) the removal of the heterogeneous catalyst from the product was difficult. Since the problems could not be solved by selection of a solvent mixture compatible to both nitrated and denitrated forms, it was first considered that the use of a homogeneous hydrogenation catalyst might outweigh the adverse effect of the formation of a solid phase in the reaction and also permit separation from the denitrated polymer.

Cupric or cuprous acetate was used in pyridine solution by Calvin (10) and by Weller and Mills (33) to catalyze the reduction of quinone to hydroquinone. Although pyridine caused extensive decomposition of cellulose nitrate (13, 29), the pentanitrates of mannitol and dulcitol were stable to the base at room temperature (15, 21). D-Mannitol-1,2,3,5,6-pentanitrate in a homogeneously catalyzed hydrogenation in pyridine with cupric acetate consumed a small and

TABLE III

ANALYSES OF CELLULOSE NITRATE SAMPLES

Cellullose nitrate	% N	% Ash	D.S.*	M†	Method of preparation
A	13.37, 13.24	0.162	2.72	285	100% $HNO_3+P_2O_5$(29)
B	12.11, 12.15	0.075	2.30	265	Hydrogenolysis of A
C	10.72, 10.65‡	0.162	1.88	247	N_2O_5 in $CHCl_3$ (9, 32)
D	2.73, 2.77	2.1	1.25§	218§	Hydrogenolysis of C
E	12.40, 12.54	0.053			

Degree of substitution $= \dfrac{3.60 \times \%\ \mathrm{N}}{31.13 - \%\ \mathrm{N}}$ (24).

†*The submolecular weight of the nitrated pyranose residue* $= \dfrac{5046}{31.13 - \%\ \mathrm{N}}$ (24).

‡*By semimicro nitrometer, other* N *values by modified micro-Kjeldahl method* (29).

§*Calculated for the total product,* D *plus* E.

uncertain amount of hydrogen and was not completely denitrated. The only crystalline organic product isolated appeared to be a copper salt of a strong organic acid and was not investigated further.

In a second attack on problem (*b*), cellulose nitrate samples A and C (Table III) were hydrogenated over Raney nickel catalyst, the nickel being removed from the hydrogenated mixture at the end of the reaction by means of a magnet. Cellulose nitrate A gave a fibrous product, cellulose nitrate B, in 82% yield based on the nitrate–nitrogen analysis. The ash content of B was negligible and the D.S. value of 2.30 indicated that denitration had been achieved to the extent of 0.42 nitrate groups per pyranose unit. Cellulose nitrate C under similar conditions gave a suspension of cellulose nitrate D in a solution of a more highly substituted cellulose nitrate E. The D.S. value of the total product (D plus E) again indicated a substantial denitration of 0.63 nitrate groups per glucose unit and the improved total yield of 98% (based on the analyses) could be attributed to the lower solubility and hence better recovery of the less highly substituted product.

It was concluded that the hydrogenation method holds promise for achieving complete polymer-analogous denitration of polysaccharide nitrates and warrants further study.

EXPERIMENTAL

Materials and Methods

The usual precautions (16, 21, 29) were observed in handling the high explosive nitrated compounds.

Cellobiose octaacetate was prepared from cotton wool and deacetylated in 82% yield to give pure cellobiose after four recrystallizations from aqueous methanol; m.p. 242°C., $[\alpha]_D^{20}$ from +22.29 to +34.45° (*c*, 4; water); the previously reported constants are shown in Table II. Nitration of cellobiose and of maltose with nitric–sulphuric acids (36) at 0°C. gave the crystalline octanitrates (Tables I and IV) in 64 and 40% yields respectively after purification

TABLE IV

NITROGEN ANALYSES OF MODEL COMPOUNDS

Carbohydrate nitrate	Found, % N	Calc., % N	Method*
Cellobiose octanitrate	15.78, 15.82	15.92	(*a*)
Maltose octanitrate	15.72, 16.46	15.92	(*b*)
D-Mannitol hexanitrate	18.30, 18.57	18.55	(*a*)
D-Mannitol-1,2,3,5,6-pentanitrate	17.28, 16.79	17.23	(*a*)
Methyl-β-D-gluco-pyranoside tetranitrate	14.53, 14.59	14.56	(*b*)

*(*a*) = *Semimicro Dupont nitrometer* (*29*).
(*b*) = *Modified micro-Kjeldahl* (*29*).

by the method of Ashford *et al.* (2) with care to keep the temperature below 30°C. during evaporation. The other model compounds were prepared as previously described (7, 15, 16).

Absorbent cotton was extracted in a Soxhlet apparatus for successive two-day periods with 1:2 ethanol–benzene and then with ligroin and dried for one month at 56°C. *in vacuo* over phosphorus pentoxide. One half to one gram samples of the bone-dry cellulose (copper number 0.247) were nitrated in 92 to 100% yield (based on nitrogen analyses) as noted in Table III. The nitrates were washed free of acids with 50% ethanol at −10°C., stabilized by refluxing with ethanol (29), and dried *in vacuo*; the analyses are reported in Table III.

The catalytic hydrogenation of the model compounds (Table II) confirmed their identity and followed the procedure described in earlier publications (15, 16, 20).

Reduction with Grignard's Reagent

D-Mannitol hexanitrate (0.93 gm.) dissolved in anhydrous tetrahydrofuran (20 ml.) was added to a cold solution of methyl magnesium iodide prepared in 50 ml. of anhydrous ether from 6.6 gm. of methyl iodide and 1.13 gm. of magnesium turnings (17). After 24 hr. at room temperature the reaction mixture was treated with water (50 ml.) and glacial acetic acid (5 ml.) and extracted with ether. Evaporation of the ether extract left a yellow sirup (0.21 gm.) which gave a positive diphenylamine test. The aqueous solution was evaporated under reduced pressure and the solid residue was acetylated at room temperature with pyridine (25 ml.) and acetic anhydride (25 ml.). Free iodine was liberated in an exothermic reaction on contact of the residue with these reagents and was removed by treatment with 10% sodium thiosulphate solution after the acetylation mixture had been diluted with ice water. Extraction of the aqueous mixture with chloroform and evaporation of the dried chloroform solution yielded crystalline D-mannitol hexaacetate (0.30 gm.) which melted at 114–116°C. after two recrystallizations from aqueous ethanol; a mixed melting point with authentic D-mannitol hexaacetate was 113–116°C.

Cellobiose octanitrate (0.95 gm.) when treated with the Grignard reagent in a similar manner yielded an ether-soluble, partially nitrated sirup (0.17 gm.) and crystalline cellobiose octaacetate (0.10 gm.) melting at 207–214°C.; the mixed melting point with authentic cellobiose octaacetate (m.p. 229.5°C.) was 219°C.

Reduction with Lithium Aluminum Hydride

Twenty milliliters of a solution of lithium aluminum hydride in ether (98.3 gm. per liter) was stirred magnetically in a two-necked flask fitted by ground glass joints with a reflux condenser and a dropping funnel. A slow stream of nitrogen was passed continuously over the solution while D-mannitol hexanitrate (0.95 gm.) in dioxane (20 ml.) was admitted dropwise through the funnel and the exothermic reaction was controlled by external cooling. After the addition was complete the mixture was stirred for a further three hours at 0°C. and then refluxed for one half hour. At the end of this time ethyl acetate (10 ml.) was added to decompose any remaining hydride, and this was followed by the addition of wet ether and then water. Separation and evaporation of

the ether layer yielded a brown sirup (0.05 gm.) which gave a positive diphenylamine test. Acetic acid (10 ml.) was added to the aqueous solution which was then evaporated. The solid residue was acetylated and worked up with chloroform to give a pale yellow sirup (0.79 gm.) which crystallized on standing. After recrystallization from aqueous ethanol the product melted at 119°C. and did not depress the m.p. of D-mannitol hexaacetate. The yield of D-mannitol from the denitration reaction amounted to 87% of the theoretical value.

Reduction with Hydrogen and Cupric Acetate in Pyridine

D-Mannitol-1,2,3,5,6-pentanitrate (0.97 gm.) and cupric acetate (0.44 gm.) were dissolved in pyridine (100 ml.) and the solution was shaken with hydrogen at room temperature and 55 p.s.i. for 24 hr. At the end of this time, blue, water-soluble crystals were observed on the walls of the reaction vessel and were washed into the pyridine solution, which was then evaporated to dryness under reduced pressure. The residue was taken up in water, and the aqueous solution was freed of copper by treatment with hydrogen sulphide and then extracted with ether. Evaporation of the ether solution left a brown, nitrate-containing sirup (0.27 gm.) and evaporation of the aqueous layer gave a crystalline product (0.32 gm.) which melted at 75–91°C., caused the evolution of carbon dioxide from sodium bicarbonate solution, and gave a positive diphenylamine test. An aqueous solution of the crystalline material was acid to Congo red.

In blank runs cupric acetate and mannitol pentanitrate, separately dissolved in pyridine, consumed no hydrogen at 25°C. and 55 p.s.i. during 24 hr.

Reduction of the Cellulose Nitrates

Cellulose nitrate A (Table III) (0.53 gm.) dissolved in ethylene glycol monomethyl ether (50 ml.) was hydrogenated for 46 hr. at 56 p.s.i. with Raney nickel catalyst. The product was a black suspension to which was added acetone (150 ml.) and the mixture was stirred for an hour over a magnet (field strength 4845 gauss) which attracted the nickel to the bottom of the reaction vessel. The clear supernatant liquid was decanted from the catalyst while the bottom of the vessel remained in contact with the magnet and the nickel was washed three times with acetone by this procedure. The washings were added to the original solution which was then poured with stirring into cold water (1 liter). The precipitated cellulose nitrate was recovered on a glass filter and washed with cold water, pressed, and then dried *in vacuo* for three days over phosphorus pentoxide. The mass of dry, coarse, white fibers (0.40 gm.) was analyzed for ash and nitrogen (cellulose nitrate B, Table III).

Cellulose nitrate C (0.66 gm.) was hydrogenated by the above procedure for 24 hr. and after separation of the catalyst the product appeared as a suspension of cellulose nitrate in a solution of a more highly substituted cellulose nitrate. The suspended fibers (cellulose nitrate D) were recovered by centrifugation, washed with acetone, dried (yield 0.26 gm.), and analyzed (Table III). The combined centrifugate and washings were worked up as described for cellulose nitrate C and the white fibrous product (0.31 gm.) was similarly dried and analyzed (cellulose nitrate E).

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REACTIONS OF ARYLSULPHONIC ESTERS

IV. AN INTERPRETATION OF SOLVOLYTIC ACTIVATION ENERGIES[1]

By J. B. Hyne[2] and R. E. Robertson

ABSTRACT

A semiempirical equation is presented relating the activation energies of some fifty solvolyses of benzenesulphonic esters to physical properties of the solvolyzing medium. The equation predicts more than 70% of these activation energies to better than 300 cal./gm-mol. The significance of the equation is discussed on the basis of a continuous spectrum of mechanisms intermediate between the accepted S_N1 and S_N2 types. A suggested interpretation of the log PZ (activation entropy) term is also offered.

INTRODUCTION

The postwar years have seen marked advances in the theory of the mechanism of solvolytic reactions. Stemming largely from the S_N1, S_N2 mechanistic classification of Hughes, Ingold, and co-workers (19) development and modification of the original hypothesis has led to significant advances in this field of reaction kinetics. Further development has been based upon a free energy interpretation of solvolytic reactions, foremost in this field being Hughes, Ingold, and co-workers (8), Grunwald and Winstein (12, 13), Swain and co-workers (30, 31), Hudson and co-workers (2, 4), and Tommila and co-workers (33, 34, 35). Particular note, however, must be taken of the work of Moelwyn-Hughes *et al.* (9, 23, 24, 25) whose efforts in this field have been directed toward an interpretation of the temperature dependence of solvolytic rates of reaction.

In recent years, there has been a growing interest in the possibility that the accepted S_N1 and S_N2 mechanisms may only be the limiting cases in a continuously varying range of mechanisms. Unambiguous evidence of such behavior is difficult to obtain but many workers have found indications that such a situation does exist (see Theoretical, 2). Doering and Zeiss (6) have outlined in considerable detail the energetics of such intermediate mechanisms. Gold (10), on the other hand, has presented evidence which is claimed to be inconsistent with a unique intermediate mechanism.

We have interpreted the activation energies of the solvolyses of benzenesulphonic esters in hydroxylic solvents upon the principle of a continuous spectrum of intermediate mechanisms varying between the two limits of S_N1 and S_N2. The principle of such "hybrid" mechanisms must, of necessity, be open to critical argument but we feel that there is sufficient significance in the point of view to be presented to warrant its consideration as a development in the general theory of solvolytic reaction mechanisms.

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[2]*National Research Council of Canada Postdoctorate Fellow, 1954-56.*

RESULTS

In Table I are collected the activation energies interpreted in this paper. These values have been recalculated from the original rate data and in some cases differ by a few per cent from the values given in the origin reference. The bulk of the work was carried out in this laboratory although in one or two

TABLE I

SOLVOLYTIC ACTIVATION ENERGIES, LOG PZ FACTORS, AND α VALUES

1 Ester*	2 Solvent	3 α	4 E_a(obs.), cal./gm-mol.	5 E_a(calc.), cal./gm-mol.	6 ΔE_a	7 t_m, °C.	8 log PZ_{obs}	9 Ref.
Me-*p*H	H_2O	0	20520	20470	50	62	10.181	22
	MeOH		20973	21264	−291	60	9.317	26
	EtOH		20400	20354	46	80	8.847	22
	*i*PrOH		19150	19414	−264	63	7.870	18
Me-*p*Me	H_2O	15	21038	21192	−154	62	10.369	27
	MeOH		21390	21987	−597	50	9.494	26
	EtOH		20944	21076	−132	66	8.988	26
	*n*PrOH		20882	20161	721	66	8.863	28
	*i*PrOH		19500	20137	−637	74	7.806	28
	*n*BuOH		19415	19144	271	80	7.896	28
	*i*BuOH		18559	19029	−470	80	7.259	28
	*s*BuOH		17964	19238	−1274	80	6.662	28
	*i*AmOH		18593	18085	508	90	7.314	28
	β-PhEtOH		18243	17454	789	90	6.813	28
Et-*p*H	H_2O	19	21040	21384	−344	62	10.500	22
	MeOH		22180	22179	1	70	9.819	26
	EtOH		21380	21269	111	80	9.107	22
Et-*p*Me	H_2O	34	21581	22007	−426	62	10.699	29
	MeOH		22800	22902	−102	67	9.925	26
	EtOH		21980	21991	−11	67	9.208	26
	*i*PrOH		21400	21076	324	68	8.470	28
*i*Pr-*p*H	H_2O	42	22659	22492	167	17	13.424	22
	MeOH		23000	23287	−287		11.130	35
	EtOH		22950	22377	573	60	10.627	22
	*i*PrOH		21630	21437	193		9.252	35
*i*Pr-*p*Me	EtOH	55	22900	23003	−103	65	10.400	26
*n*Pr-*p*H	H_2O	26	21500	21722	−222	62	10.520	22
	EtOH		21669	21606	63	73	9.050	22
*n*Bu-*p*H	H_2O	10	20530	20951	−421	50	10.040	22
	EtOH		20941	20835	105	90	8.587	22
*i*Bu-*p*H	H_2O	63	23494	23504	−10	73	11.483	22
	EtOH		23212	23388	−166	73	8.949	22
*n*Pen-*p*H	H_2O	11	20700	20999	−299	50	10.173	22
	EtOH		21082	20883	199	87	8.712	22
Me-*p*Br	MeOH	7	21150	21601	−451	57	9.863	26
	EtOH		20773	20691	82	56	9.420	26
	*i*PrOH		19797	19751	46	61	8.600	28
Et-*p*Br	EtOH	26	21596	21606	−10	61	9.410	26
*i*Pr-*p*Br	MeOH	47	23200	23528	−328	47	11.522	26
	EtOH		22330	22618	−288	65	10.652	26
	*i*PrOH		21600	21578	22	62	9.700	28
Me-*p*NO_2	EtOH	9	20730	20787	−57	55	10.000	26
Et-*p*NO_2	EtOH	29	21680	21750	−70	57	10.247	26
*i*Pr-*p*NO_2	EtOH	50	22880	22762	118	60	11.661	26
Me-*m*NO_2	EtOH	6	20690	20643	47	55	10.062	26
Et-*m*NO_2	EtOH	24	21338	21510	−172	57	10.104	28
Me-*p*F	H_2O	13	21027	21095	−68	60	10.581	28
Me-*p*MeO	H_2O	20	21500	21433	67	55	10.375	28
	EtOH		21080	21317	−237	80	8.927	26
Et-*p*MeO	EtOH	36	21848	22088	−240	80	9.071	26

**Method of notation of esters will be obvious from the following: Me-pH = methyl benzenesulphonate; Me-pMe = methyl p-methyl benzenesulphonate.*

cases results of Tommila and co-workers are used. In the majority of cases where comparison is possible agreement with other work is good. No experimental details are given since these have been previously presented with the rate data in the origin references.

Table I shows for each ester (column 1) in each solvent (column 2) an observed (column 4) and calculated (column 5) activation energy and the difference between the two values (column 6). The observed log PZ term (column 8) is also recorded. Column 3 records an α value, characteristic of the ester, the physical significance of which is discussed later. The mean of the temperatures at which the individual rate determinations were made is shown in column 7. In those cases where this mean is considerably different from the average value the possibility of error due to neglect of temperature dependence of activation energy must be considered (see section—Interpretation of Activation Energies). In the majority of cases the observed activation energy may be quoted to better than ±200 cal./gm-mol. Column 9 gives the origin reference. The dielectric constants and molecular volumes of solvents used in the evaluation of the calculated activation energy are shown in Table II. The dielectric constant at 20°C. was employed as this was the most convenient temperature for obtaining data for the less common solvents. As the D value is used only as a measure of relative solvent dielectric strength, this introduces no serious error.

TABLE II

DIELECTRIC CONSTANTS AND MOLECULAR VOLUMES OF SOLVENTS

Solvent	D	t, °C.	Ref.	MV
H_2O	80.4	20	(1)	18
MeOH	32.4	20	(1)	40
EtOH	25.0	20	(1)	58.4
*n*PrOH	20.8	20	(1)	74.6
*i*PrOH	18.6	20	(1)	76.5
*n*BuOH	17.8	25	(20)	91.5
*i*BuOH	18.7	20	(20)	92.5
*s*BuOH	15.5	19	(20)	91.7
*i*AmOH	15.3	23	(20)	108.6
β-PhEtOH (value for benzyl alcohol)	13.0	20	(11)	119.4

THEORETICAL

1. *Nucleophilic Substitution Mechanisms*

The S_N1 and S_N2 mechanisms introduced by Ingold and Hughes (14, 15, 16) are now widely accepted as a firm base on which further work on the mechanism of nucleophilic substitution reactions may be developed. A brief resume of the principles involved in these mechanisms is of value here. S_N1 takes place through the formation of an intermediate ionic state, the ions being stabilized by solvation. Formation of the ionic intermediate is the rate

$$A - B \underset{slow}{\rightarrow} [\text{Transition State}] \rightarrow \underset{\text{Intermediate}}{[A^+ + B^-]} \overset{C}{\underset{fast}{\rightarrow}} [\text{Transition State}] \rightarrow \text{Product}$$

determining stage in the reaction. The rates and activation parameters measured are therefore associated with the formation of the first transition state. S_N2, in contrast to the S_N1 mechanism, is often referred to as a single

$$A - B + C \rightarrow \underset{\text{Transition State}}{[A- -B- - -C]} \rightarrow \text{Products}$$

stage reaction. The reactant AB does not undergo preliminary dissociation before reacting with component C; scission of the AB bond and formation of the CB bond take place simultaneously in the transition state.

Criteria for distinguishing between these mechanisms have been proposed and discussed by many workers (14). The failure of these criteria to establish the mechanism of certain reactions has led to the proposal by several workers of mechanisms intermediate between S_N1 and S_N2.

2. *Evidence for Intermediate Mechanisms*

Following upon the initial exploitation of the S_N1 and S_N2 mechanistic theory examples were found of reactions which exhibited phenomena typical of both S_N1 and S_N2 mechanisms. Bateman, Hughes, and Ingold (3) established a criterion for mechanism based upon the relationship of product ratio and rate in mixed solvolysis. In cases where such a relationship existed an S_N2 mechanism was found to explain the observed dependence and in the absence of any relationship, as for *tert*-butyl chloride in aqueous alcohol, an essentially S_N1 mechanism was proposed. The operative word here is "essentially" since there is only evidence for a charged intermediate in the *tert*-butyl chloride case, not for the separable ions of the pure S_N1 mechanism. The indications are, therefore, that although the mixed solvolysis of *tert*-butyl chloride does not conform to S_N2 mechanics, there is little evidence to support the conclusion that it proceeds by a pure S_N1 mechanism. Swain and Moseley (31) have illustrated this point by comparing the rates of solvolysis of triphenylmethylfluoride, *tert*-butyl chloride, and *n*-butyl bromide and showing that the mechanistic behavior of *tert*-butyl chloride is intermediate between that of triphenylmethylfluoride (S_N1) and *n*-butyl bromide (S_N2).

The influence of bulk dielectric constant of the medium upon reaction rate has also been employed as a criterion of mechanism. Since the formation of the ionic intermediate in the S_N1 case is more dependent upon dielectric of the medium than the covalent bond-making, bond-breaking process of the S_N2 mechanism, it is generally accepted that the rates of S_N1 reactions are more markedly affected by change in dielectric constant than those of S_N2 reactions (19). A clear-cut boundary between S_N1- and S_N2-type reactions would therefore be expected to lead to a similarly clear-cut grouping of reaction rates highly dependent on dielectric constant and those less markedly dependent. Such behavior has been observed by Cowan, McCabe, and Warner (5) for several solvolytic reactions plotting k vs. $(D-1)/(2D+1)$, but the group exhibiting the most marked dependence of rate on dielectric constant included *tert*-butyl chloride for which there is strong evidence of an intermediate type of mechanism. Archer and Hudson (2), in their work on the solvolysis of acid chlorides, have shown that the rate dependence on dielectric constant under-

goes a marked increase as the aqueous content of the acetone/water solvent increases. These authors considered this behavior as evidence of a change of mechanism from S_N2 to S_N1 but there is no indication that the change is sudden. Rather do the data support the idea that the mechanism is continuously changing from an "S_N2-like" mechanism at low water content to an increasingly "S_N1-like" mechanism. Grunwald, Winstein, and Jones (13) have applied their correlation of solvolysis rates to the investigation of solvolytic systems belonging to the so-called "borderline" class of mechanisms and have shown that interpretation of rate behavior in terms of two different simultaneous processes is not possible. They conclude that there is a unique mechanism operative in these "borderline" cases. Brown and Hudson (4) also illustrated the well-established dependence of activation energy upon mechanistic type. In the solvolysis of benzoyl chloride, for example, the activation energy increases continuously as the ionizing power of the medium increases and the mechanism becomes more "S_N1-like".

Doering and Zeiss (6) provide stereochemical evidence for intermediate mechanistic behavior in their studies of the methanolysis of optically active hydrogen 2,4-dimethylhexyl-4-phthalate where solvolysis is accompanied by roughly 50% racemization and 50% inversion.

There is then no lack of evidence to suggest that the original S_N1, S_N2 mechanistic classification represents but the extreme limits of a whole range of possible intermediate mechanisms.

3. *S_N12 Intermediate Mechanisms*

As a tieback for the present work we make special reference to the paper of Doering and Zeiss (6). The idea of a complete range of mechanisms between the limiting cases of S_N1 and S_N2 involving an intermediate of varying stability has been clearly expounded by these authors. Henceforth, we shall refer to such intermediate mechanisms as S_N12. Our development of the intermediate mechanism, with a view to explaining the kinetics of benzenesulphonic ester solvolysis, is, in essence, similar to the Doering and Zeiss hypothesis although there are several differences in detail.

In the accepted S_N2 mechanism bond breaking in the ester molecule and covalent interaction of the ester with the solvent molecule occur simultaneously. If we envisage the covalent interaction entering progressively later in the reaction path, in the limit bond breaking in the ester molecule will proceed to completion with the formation of solvation stabilized ions before covalent interaction with the solvent takes place. This limiting case is in fact the condition characteristic of an S_N1 mechanism. The S_N12 spectrum of intermediate mechanisms occupies this range between S_N2 and S_N1 brought about by the increasing interval between commencement of bond breaking in the ester and onset of covalent interaction with the solvent. It is not unreasonable to assume, moreover, that a solvation stabilized intermediate will exist without the actual formation of ions. A solvation stabilized intermediate ester species may then be envisaged in which there is charge separation in the ester bond eventually to undergo scission. The stability of this intermediate will be greater the greater the charge separation, i.e. the more "S_N1-like" the S_N12

mechanism becomes. As the S_N2 end of the S_N12 spectrum is approached, however, the onset of covalent interaction becomes progressively nearer to the onset of charge separation in the reaction path. A very unstable intermediate will then be formed and in that region of the spectrum of S_N12 mechanisms very close to the S_N2 type the intermediate may have no real stability. The position occupied on the S_N12 spectrum of mechanisms by the series of benzenesulphonic ester solvolyses studied in this work cannot be firmly established on the evidence available. We have assumed, however, that even in the most "S_N2-like" reaction mechanism, namely, the solvolysis of methyl benzenesulphonate, there is a real intermediate formed albeit of low stability. In discussing the application of the S_N12 mechanism to the solvolysis of benzenesulphonic esters, therefore, we have not considered that part of the S_N12 range near the S_N2 end where there is no actual existence of an intermediate.

In the S_N12 mechanism as applied to these solvolytic reactions the charge separated intermediate is reached through a transition state, the formation of which is the rate determining step in the S_N12 mechanism. The charge separated intermediate is stabilized through solvation by molecules of the solvolyzing

$$A - B \xrightarrow[slow]{} [\text{Transition State}] \rightarrow \underset{\text{solvated}}{[A^{\delta-} - - - B^{\delta+}]} \xrightarrow[fast]{C} \underset{\text{Transition State}}{[A - - B - - C]} \rightarrow \text{Products}$$

medium and the extent of charge separation in the intermediate is the determining factor in placing the mechanism in its relative position in the range between the limiting S_N1 and S_N2 cases. Since all observed rates and derived activation parameters provide information only on the rate determining stage, the mechanism of the subsequent reaction of the intermediate with C to give products cannot be supported, at this stage, by experimental facts. We can say, however, that during this second activation process one of the molecules involved in the solvation of the intermediate must become covalently bonded to the intermediate to form the second transition state. In a subsequent paper (18) we deal with the interpretation of the solvolysis of benzenesulphonic esters in *mixed* solvents where the question of the detailed nature of the solvation and the second transition state is more fully discussed.

In the present picture the distance along the reaction parameter r (Fig. 1) at which covalent interaction becomes important determines the relative position of the first transition state (T_{cs} = charge separated transition state) with respect to the second transition state (T_c = covalent transition state). When the two transition states are coincident the mechanism is S_N2 with no intermediate (curve (1), Fig. 1). As covalent interaction between solvent and reacting solute enters further along the reaction parameter r, a solvation stabilized intermediate will appear, the stability of the intermediate increasing as the point of entry of covalent interaction is further removed from the charge separated transition state. This whole range of varying stability of intermediates of increasingly greater charge separation represents the spectrum of S_N12 mechanistic types. One such S_N12 mechanism is depicted in Fig. 1,

curve (2). Eventually, covalent interaction enters so far along the reaction parameter r that the charge separation in the intermediate proceeds to complete ionization with solvation stabilization of the ions and the mechanism becomes limiting S_N1 (Fig. 1, curve (3)). The relative heights of the first maxima in the three curves of Fig. 1 are without significance as drawn. This point is considered in greater detail in Fig. 6 with specific cases from the benzenesulphonic ester solvolyses. It will be noted from Fig. 1, however, that the second, or covalent transition state, T_c, is at a lower energy level than the first, or charge separated transition state, T_{cs}, in each curve since the attainment of the first transition state is the rate determining process. Further, the height of the second energy barrier approaches that of the first as the mechanism moves through the S_N12 range from S_N1 to S_N2 until the two transition states become one in S_N2. This is in keeping with the picture of *decreasing* charge separation in the intermediate on moving from S_N1 to S_N2 since it will require greater activation energy to bring about covalent interaction between the decreasing charge separated intermediate and the dipolar solvent molecule.

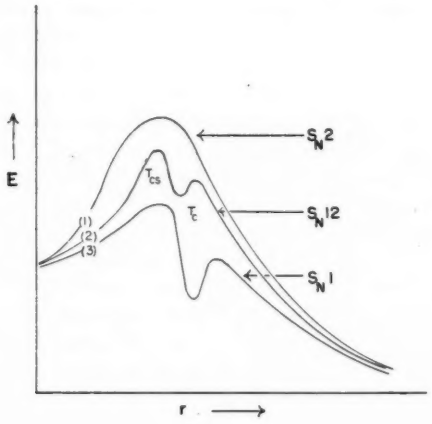

FIG. 1.

INTERPRETATION OF ACTIVATION ENERGIES

1. *Aim*

In the tables of results previously presented we have collected the experimentally determined activation energies of some fifty solvolytic reactions of benzenesulphonic esters. On the basis of the S_N12 mechanism outlined in the foregoing section we have established an equation from which these activation energies may be calculated with a precision well within the experimental error associated with the determinations. Previously published work from this laboratory (17, 27) has shown that the temperature dependence of the activation energy of such solvolytic reactions is significant and the fact that this dependence has not been taken into account in this study must be borne in mind. The

determination of the temperature dependence of the activation energies used in this correlation is now in progress in this laboratory but in view of the lengthy nature of this work it is unrealistic to assume that neglect of this factor seriously detracts from the value of presenting the treatment in its present form. Furthermore, the agreement between observed and calculated values of the activation energies is such as to suggest that any error introduced through neglect of the temperature dependence is minimized by the particular set of conditions obtaining in the series of activation energies presented. Those few cases where agreement is poor may be due to neglect of this factor.

2. *Components of the Activation Energy*

The observed activation energy of the S_N12 mechanism is, by definition, associated only with the first, charge separated, transition state. Consider the factors which would be expected to lead to the difference in energy between the initial and transition states. Any component of the over-all activation energy resulting from covalent interaction between ester and solvent molecules in the initial rate determining transition state will be negligible as a result of the assumed position of the range of these solvolytic mechanisms on the S_N12 spectrum; that is, covalent interaction in the initial transition state is very small. Energy, however, will be required to bring about charge separation in the ester bond eventually to undergo scission; this component of the activation energy we denote as E_e. That the initial state of the system involves solvation of the ester cannot be denied; the charge separation created in the transition state, however, will result in greater attractive force being exerted by the ester molecule on the solvent molecules leading to an increase in extent of solvation in the transition state. *To a first approximation* the nature of solvation of the ester molecule at points other than around the seat of reaction ($-SO_3$ group) may be assumed to be the same in the initial and transition states so that the difference in extent of solvation will be largely centered on the SO_3 group. Solvent molecules, therefore, must be removed from the solvent lattice to be available for their solvating role. This component of the activation energy we denote as E_s. We now have $E_a = E_e + E_s$. The two components of E_a must now be related to some measurable parameters of the system in order to obtain an expression for E_a. Consider firstly E_e—the energy required for charge separation in the reactive bond. For any given ester this must be related to the dielectric constant of the surrounding medium. We at once recognize that the bulk dielectric constant of the solvent medium is not truly representative of the localized dielectric in the immediate vicinity of the created partial charges. Some measure of success has previously been achieved with relations involving the bulk dielectric constant, however, and in the absence of a better measure of dielectric of the medium we employ the bulk dielectric constant, bearing in mind this possible source of error. We then have $E_e = f(D)$. The solvation energy component E_s does not lend itself to such simple interpretation as E_e. The number of solvent molecules which can be accommodated in the first solvation shell (that largely determining E_s) must be a function of the molecular volume of the solvent species. The increased solvation of the transition state requires rupture of solvent–solvent bonds in the solvent lattice to free the molecules for their solvating role. We now make the assump-

tion, again bearing in mind a possible source of error, that in the hydroxylic solvents all solvent–solvent hydrogen bonds, being of the O—H- - -O type, are of the same energetic magnitude. Therefore the increase in number of solvent molecules in the solvation shell of the transition state will be a relative measure of the solvation energy which, in turn, must be related to the molecular volume of the solvent species; let this be an $E_s = f(MV)_s$ proportionality. E_a may then be expressed as $E_a = f(D) + f(MV)_s$. We must now attempt to find the nature of these functions. It is not denied that the form of the functions may be derivable on a theoretical basis. Since, however, we are primarily interested in establishing only a quantitative expression for E_a we have adopted an empirical approach.

It is noted that the E_a's for the solvolysis of methyl benzenesulphonate in water and in ethanol are almost the same. If $f(D)$ and $f(MV)_s$ are to be the only variables in the equation, then their relative values must be adjusted by constant multipliers such that the E_a's for these two solvolytic reactions are the same. This empirical approach led to the derivation of a constant multiplier for the $(MV)_s$ term = 1.43, and E_a for the methyl benzenesulphonate solvolysis in several solvents was plotted against $(D+1.43(MV)_s)$. A straight line equation of the form

$$E_a = a(D+1.43(MV)_s)+b \qquad [1]$$

was obtained where $a = -48.17$ and $b = 25{,}580$.

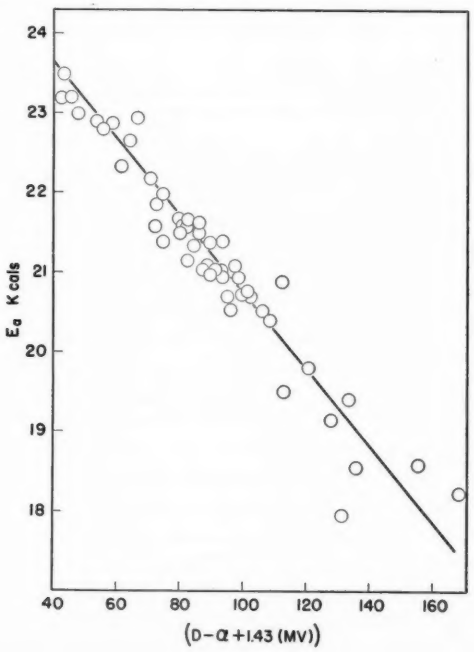

FIG. 2.

3. *The α Value—Measure of Charge Separation*

On plotting the available activation energy data (Table I) against $(D+1.43(MV)_s)$ it was found that for each ester a straight line was obtained in accordance with equation [1]. The lines were all of the same slope but displaced along the $(D+1.43(MV)_s)$ axis. This was not surprising considering that when the relationship between E_s and D was discussed no account was taken of the variation of the ester species. The energy required to bring about charge separation in the transition state must be, to a considerable extent, dependent upon the groups on the reactive center of the ester. Such an effect cannot be measured by D since this is purely a property of the solvent medium. There is, of course, the possibility that the solvation energy, E_s, may vary with the extent of charge separation in the ester. We feel, however, that the important controlling factor in solvation is the molecular volume since in the range of compounds studied the difference in charge separation may not be too great and the size of the solvating species dominates the solvation effect.

A constant correction factor, α, for each ester was applied to the D value such that the plot of E_a vs. $(D-\alpha+1.43(MV)_s)$ became coincident with the methyl benzenesulphonate line. The equation

$$[2] \qquad E_a = -48.17(D-\alpha+1.43(MV)_s)+25{,}580$$

was found to predict some 70% of fifty E_a's to better than 300 cal. This accuracy of prediction is comparable with the experimental error in E_a's for the majority of the reactions. The E_a's vary over some 6000 cal.

Undoubtedly the most interesting features of this correlation are the resultant α values. On the basis of the present theory (we suggest) they represent the relative magnitude of the charge separation in the transition states of the esters studied, based on the arbitrary zero of methyl benzenesulphonate. This does not mean, of course, that there is no charge separation in methyl benzenesulphonate. The α values derived are collected in Table III.

The effect on the α value of changing the complexity of the ester alkyl group (R) is clearly seen in Fig. 3. This effect appears to be independent of the *p*-group on the benzene ring as is manifest in the parallelism of the lines for esters with varying *p*-groups. The series methyl benzenesulphonate to *n*-pentyl benzenesulphonate (Table III(*a*)) plotted in Fig. 4 shows an increase in α to *n*-propyl benzenesulphonate beyond which the value decreases to a constant value. This behavior is somewhat similar to that observed by Everett, Landsman, and Pinsent (7) for the free energy and entropy of ionization of a series of fatty acids. This they attribute to chain stiffening in the longer hydrocarbon groups. Such an explanation may well be applicable to the trend in α values observed here. Creation of partial charges in the transition state will lead to repulsion of the low dielectric hydrocarbon "tail" thus reducing solvent exclusion at the reaction center in the long chain esters. Less charge separation will then be required in the transition state to effect sufficient solvation to stabilize the intermediate—hence the lower value of the α term. The series of α values corresponding to variation of the *p*-group for constant ester alkyl group (Table III (*e*)) is most unexpected. We have assumed, however,

TABLE III

α VALUES FOR BENZENESULPHONIC ESTERS

Ester		α	Δα
(*a*) *p*H series			
Me-*p*H*		0	
			19
Et-*p*H		19	
			23
*n*Pr-*p*H		26	
			21
*n*Bu-*p*H		10	
*n*Pen-*p*H		11	
(*c*) *p*Br series			
Me-*p*Br		7	
			19
Et-*p*Br		26	
			21
*i*Pr-*p*Br		47	
(*e*) Me-*p*X series			
Me-*p*H	1.8†	0	
Me-*p*Br	1.7†	7	
Me-*p*NO_2	4.3†	9	
Me-*p*F	4.3†	13	
Me-*p*Me	6.2†	15	
Me-*p*MeO		20	

Ester	α	Δα
(*b*) Branched chain series		
Me-*p*H	0	
		19
Et-*p*H	19	
		23
*i*Pr-*p*H	42	
		21
*i*Bu-*p*H	63	
*neo*Pen-*p*H	(112)	
(*d*) *p*NO_2 series		
Me-*p*NO_2	9	
		20
Et-*p*NO_2	29	
		21
*i*Pr-*p*NO_2	50	
(*f*) *p*Me series		
Me-*p*Me	15	
		19
Et-*p*Me	34	
		21
*i*Pr-*p*Me	55	

**The nomenclature used in Table III will be clear from the example, Me-pH = methyl benzenesulphonate.*

†*Heat of solution in kcal. of corresponding benzenesulphonic acids in water.*

as a first approximation (see Section 2), that the nature of solvation of the ester molecule at points other than the seat of reaction, the SO_3 group, is relatively the same in both the initial and transition states. This approximation may not be valid when dealing with the effect of *p*-groups since in addition to the intramolecular effect of such groups on the reaction center they may also lead to different solvation at points other than the SO_3 group in the initial and transition states. One interesting comparison which may have significance is that of the α values for these *p*-groups with the heat of solution of the corresponding benzenesulphonic acids (32). This is illustrated in Fig. 5 where it will be noted that both the *p*-F and *p*-Br compounds lie above the line through the other points.

4. *Benzenesulphonic Ester Solvolysis by S_N12 Mechanism*

On the basis of the interpretation of activation energies we have presented, let us consider in greater detail the S_N12 mechanism as it applies to the solvolysis of benzenesulphonic esters. In Fig. 1 we considered the general relationship between S_N12, S_N1, and S_N2 reactions but did not attach significance to the relative heights of the first maxima for each curve. Let us now consider three cases *within* the S_N12 range as depicted in Fig. 6. For example, let these curves

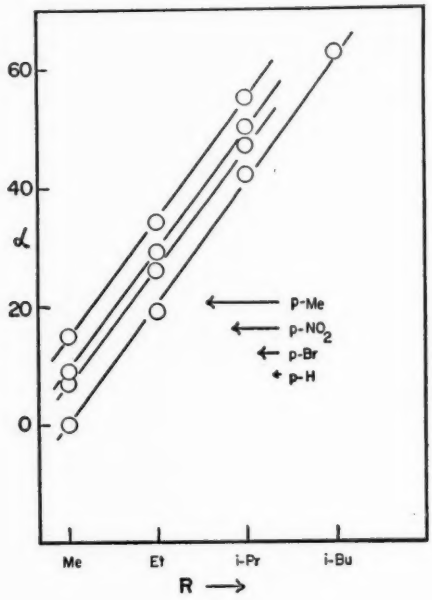

FIG. 3.

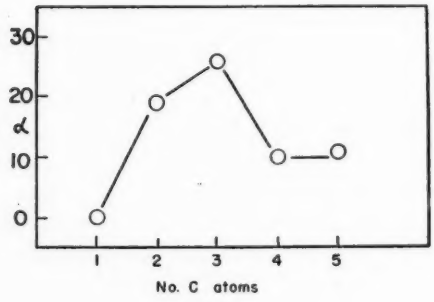

FIG. 4.

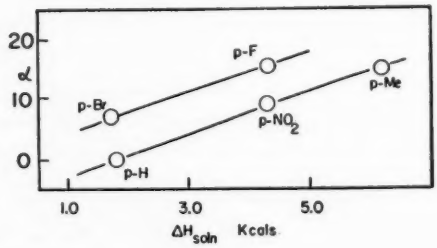

FIG. 5.

represent the relative energy vs. reaction parameter relationship for isopropyl (1), ethyl (2), and methyl (3) benzenesulphonates. In Table IV the observed activation energies and calculated α values are recorded for the hydrolysis of these three esters. Since in the S_N12 mechanism the rate and activation energy are determined in the first transition state the heights of the initial maxima in Fig. 6 are in the order isopropyl > ethyl > methyl benzenesulphonate. The α values indicate greater charge separation for greater activation energy. The greater the charge separation the greater will be the solvation

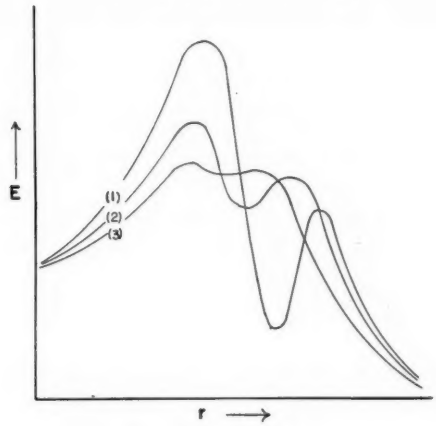

FIG. 6.

TABLE IV

Ester	E_a (cal.)	α
*iso*Pr-*p*H	22,659	42
Et-*p*H	21,040	19
Me-*p*H	20,520	0

stabilization and hence the deeper the intermediate minimum leading in the extreme to the formation of solvation stabilized ions (S_N1). The onset of covalent interaction between solvent molecules and charge separated ester species occurs at an earlier stage along the reaction parameter r as we proceed down the series isopropyl, ethyl, methyl, this covalent interaction requiring higher activation energy as the intermediate becomes less ionic in character. Eventually covalent interaction will enter at such an early stage that an appreciable amount of solvent–solute covalent interaction will take place in the first transition state and the mechanism will become S_N2 in character.

DISCUSSION OF SOLVOLYTIC ACTIVATION ENTROPIES

Discussion of activation entropy must be restricted to a comparison within a series of systems, since in the absence of a knowledge of the collision number we are confined to the use of log PZ as a relative measure of the activation

entropy (21). We may assume, however, that as log PZ decreases, ΔS becomes a larger negative quantity indicating a greater increase in ordering on moving from initial to transition state.

1. *Series of Varying Ester in Given Solvent*

For the straight chain alkyl group series of esters we find the entropy difference between initial and transition state decreasing as we proceed from methyl to ethyl benzenesulphonate. Table V would indicate that the increased bulk of the ethyl group limits the extent of increase of ordering possible in the transition state despite the increase in attraction offered by the increase in

TABLE V

LOG PZ OF HYDROLYSIS OF BENZENESULPHONIC ESTERS

Ester	log PZ	α
Me-*p*H	10.227	0
Et-*p*H	10.500	19
*n*Pr-*p*H	10.500	26
*n*Bu-*p*H	10.040	10
*n*Pen-*p*H	10.173	11
*iso*Pr-*p*H	13.424	42
*iso*Bu-*p*H	11.483	63

charge separation (α value). The entropy decrease on moving to the transition state will then be less than in the methyl case. Further increase in chain length, viz. to *n*-propyl, sees the onset of chain stiffening. The solvent exclusion effect of the hydrocarbon tail in the transition state is reduced through repulsion of the *n*-propyl chain from the partial charges generated at the reaction center. The increased bulk of the *n*-propyl over ethyl is therefore counterbalanced by chain stiffening and the ΔS (or log PZ) value is approximately equal to that for ethyl; *n*-butyl and *n*-pentyl groups suffer such repulsion from the partial charges that their solvent exclusion effects and hence the ΔS values are comparable with the methyl compound. On considering the branched chain alkyl benzenesulphonic esters we find a very marked reduction in the entropy difference between initial and transition states. By a similar argument to that employed for the straight chain alkyl groups we would conclude that the solvent exclusion effect in the isopropyl case is much increased leading to a marked reduction in increase of ordering in the transition state compared with the initial state again despite the creation of greater partial charges. It is then sterically impossible to accommodate any significantly greater number of molecules in the transition state solvation shell compared with the initial state, leading to a very small entropy change. This does not deny, however, the possibility that the solvation shell molecules are held more rigidly, a phenomenon which, we feel, would be reflected more in the heat capacity change than in the entropy change. As would be expected, the isobutyl case, with branching on the β-carbon atom, shows somewhat less marked solvent exclusion reflected in the greater entropy change compared with isopropyl. It should be noted that generally speaking, the log PZ values follow the same trend as the α values.

2. *Series of Given Ester in Varying Solvent*

Let us consider the case of solvolysis of methyl *p*-methyl benzenesulphonate in a series of hydroxylic solvents (Table VI).

For a given ester the dipolar initial state will encounter increasing difficulty in ordering progressively larger solvent molecules about it in a solvation shell. As the hydrocarbon residue of the hydroxylic solvent increases in size, therefore, the entropy of the initial state will increase (Fig. 7). A similar condition will obtain in the transition state but the effect of size on degree of ordering will be somewhat reduced owing to the greater attractive force exerted on the solvent molecules by the partial charges created in the transition state. The entropy of the transition state might then be expected to increase less rapidly through the series than in the initial state (Fig. 7). On this picture it is clearly seen that the entropy decrease from initial to transition state increases on moving up the series. This is in agreement with the observed log *PZ* behavior (Table VI).

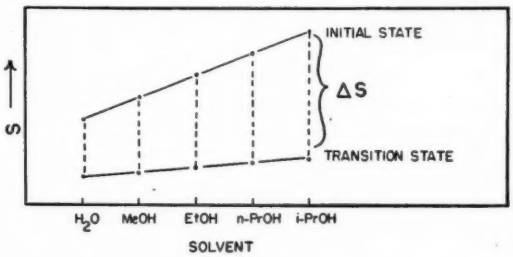

FIG. 7.

TABLE VI

LOG *PZ* OF SOLVOLYSIS OF METHYL *p*-METHYL BENZENESULPHONATE IN VARIOUS SOLVENTS

Solvent	H_2O	MeOH	EtOH	*n*PrOH	*iso*PrOH
log *PZ*	10.369	9.494	8.988	8.863	7.806

CONCLUSIONS

The validity of the interpretation of solvolytic activation energies presented in this paper is based upon the success of the derived semiempirical equation in predicting the observed activation energies. The effect of neglect of temperature dependence of activation energy has been considered and in the finer analysis of the data this may be of some importance. The general success of the equation in relating more than fifty activation energies to measurable parameters of the reaction system cannot, however, be denied. Whether the molecular pictures of the successive states occurring in the reaction mechanism proposed can be justified by direct proof of their existence is questionable at the present time. The fact remains, however, that on the basis of the mechanism proposed, physical significance can be given to the form of the semiempirical equation employed and a factor, α, can be derived, the variation of which, through series of solvolyses, appears to be in keeping with the general picture

presented. Much discussion has been centered around the validity of interpreting activation entropies in the manner here adopted. We would not deny that the definition of the physical significance of a single entropy value is a very complex problem but in discussing the significance of a series of entropy differences we feel we have some justification. If this paper does no more than provoke discussion of the mechanistic points presented it will have served its purpose.

A logical extension of the treatment of activation energy data presented here forms the basis for a further paper on solvolysis in mixtures of water with several alcohols. The success of this extension is even more striking than the present correlation and further serves to assure us that the model we have presented is a good first approximation to the truth. At this stage in the interpretation of the energetics of reaction mechanisms one can hardly expect more.

ACKNOWLEDGMENT

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ORGANIC NITRATES AS SYNTHETIC INTERMEDIATES

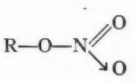
PREPARATIONS OF NITRATES AND SOME REPRESENTATIVE REACTIONS[1]

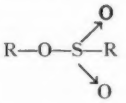
By F. L. M. Pattison and G. M. Brown[2]

ABSTRACT

It has been shown that the carbon–oxygen bond of nitrate esters is susceptible to cleavage by certain representative nucleophilic reagents, of which sodium iodide, sodium cyanide, and potassium thiocyanate have received particular attention. Allyl, 3-hydroxypropyl, 4-fluorobutyl, hexyl, and benzyl nitrate were examined in order to determine the effect if any of functional groups on the ease and efficiency of cleavage.

Alkyl and aralkyl sulphonates are well known as synthetic intermediates, undergoing most of the replacement and elimination reactions characteristic of the alkyl halides. However, their preparation, while frequently occurring in very high yield, is time consuming, and the products often have very high boiling points, making purification inconvenient. Accordingly, attention was directed to esters of other inorganic oxy-acids; these it was hoped would undergo the same reactions, due to oxygen–alkyl fission. From a superficial consideration of structure, nitrates were selected for study:





The chemistry of nitrate esters has been reviewed recently (3). Several alkylation reactions have been reported: benzyl nitrate has been used successfully in benzylating malonic and acetoacetic esters (15); methyl nitrate has been converted to the corresponding isothiouronium nitrate using thiourea (21); diphenylmethyl nitrate has been converted to N-diphenylmethylacetamide on treatment with acetamide (6); trialkylsulphonium nitrates have been formed from dialkyl sulphides and alkyl nitrates (18); amines have been alkylated using alkyl and aralkyl nitrates (9, 12, 19); and the action of sodium ethoxide on nitrates has produced ethyl ethers (4, 5). The reactions of nitrates have received most attention in the field of carbohydrates, and in at least one instance the nitrate grouping has been replaced by iodide using sodium iodide in acetone (11). No reference has been made to the replacement reactions of the nitrate grouping as a simple alternative to the use of alkyl halides in preparative organic chemistry.

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Contribution from the Department of Chemistry, University of Western Ontario, London, Ontario. Abstracted from the M.Sc. thesis submitted to the University by G. M. Brown in 1955. Issued as D.R.B. Report No. SW-25.
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Nitrates may be prepared by direct esterification of alcohols with nitric acid, or by reaction of a suitable alkyl halide with silver nitrate. However, only the first of these is of practical importance in this work, since the halides required for the second method could themselves be used directly in the replacement reactions. The direct esterification method has been reported to be very simple and to give high yields, but the conditions are sometimes critical; the halide method gives consistently good results. For convenience, both methods were employed to obtain the nitrate esters used in this work. Results are shown in Table I.

TABLE I

NITRATES: PREPARATION, PHYSICAL CONSTANTS, AND ANALYTICAL RESULTS

R in $RONO_2$	Method of preparation[a]	Yield, %	Boiling point °C.	Boiling point mm.	n_D^{25}	C, % Calc.	C, % Found	H, % Calc.	H, % Found
$CH_2{:}CHCH_2-$[b]	I	33	102–105		1.4112				
	II	49	104–106		1.4120				
$HO(CH_2)_3-$	I	49	103–104	16	1.4378	29.75	29.83	5.84	5.90
	III	76	123–125	42	1.4372				
$CH_3(CH_2)_3-$[c]	II	54	130–131		1.4031				
	III	61	130–133		1.4030				
	IV	74	130–132		1.4036				
$F(CH_2)_4-$	II	68	74–77	19	1.4060	35.03	34.82	5.89	5.88
	III	75	65	12	1.4070				
$Cl(CH_2)_4-$	III	64	92–93	11	1.4541	31.28	30.93	5.26	4.92
$CH_3(CH_2)_5-$[d]	II	83	66–70	12	1.4174				
	III	77	66	11	1.4180				
	IV	73	67–69	12	1.4182				
$F(CH_2)_6-$	II	28[h]	112	28	1.4179	43.62	43.82	7.34	7.35
$C_6H_5CH_2-$[e]	I	70	101–104	12	1.5179				
$CH_3(CH_2)_9-$[f]	IV	59	127–128	12	1.4328				
$CH_3(CH_2)_{11}-$[g]	IV	67	143–144	5	1.4380				

[a] *Methods of preparation—I: chloride+silver nitrate; II: bromide+silver nitrate; III: iodide+silver nitrate; IV: alcohol+HNO_3 and H_2SO_4.*

[b] *Henry (10) reports b.p. 106°.*

[c] *Cowley and Partington (7) report b.p. 135.7° at 770 mm. and n_D^{20} 1.4063.*

[d] *Soffer, Parrotta, and Di Domenico (20) report b.p. 46° at 1 mm. and $n_D^{24.5}$ 1.4180.*

[e] *Lucas and Hammett (13) report b.p. 72.5–73.5° at 4–5 mm. and n_D^{25} 1.5180.*

[f] *Medard and Alquier (14) report b.p. 88–89° at 1–2 mm.*

[g] *Medard and Alquier (14) report b.p. 99–100° at 1–1.5 mm.*

[h] *Low yield due to accidental loss.*

The cleavage of nitrates is significant in the main as a method of replacing –OH by different functional groups, that is, as an alternative to the use of halides or sulphonates. Some representative cleavages are shown in Table II. In addition to those listed, benzyl nitrate was treated (*a*) with sodium bromide

to form benzyl bromide in 64% yield, and (*b*) with thiourea followed by hydrolysis to form benzyl mercaptan in 32% yield. Analytical results and physical constants of new compounds are listed in Table III. The boiling points of some of the products were very similar to those of the parent nitrates, making purification difficult.

TABLE II

CLEAVAGE OF NITRATES: YIELDS (%)

Reaction	R = CH_2:$CHCH_2$–	HO$(CH_2)_3$–	F$(CH_2)_4$–	$CH_3(CH_2)_5$–	$C_6H_5CH_2$–
$RONO_2 + NaI \rightarrow RI + NaNO_3$	62	60	63	84	76
$RONO_2 + NaCN \rightarrow RCN + NaNO_3$	31[a]	—	45[a]	77[b]	68[a]; 66[b]
$RONO_2 + KSCN \rightarrow RSCN + KNO_3$	33[c]	35	57	86	86

[a] *80% Ethanol as solvent.*
[b] *Ethylene glycol as solvent.*
[c] *Allyl isothiocyanate.*

TABLE III

PRODUCTS OF CLEAVAGE: PHYSICAL CONSTANTS AND ANALYTICAL RESULTS OF NEW COMPOUNDS

	Boiling point		n_D^{25}	C, %		H, %		Other, %	
	°C.	mm.		Calc.	Found	Calc.	Found	Calc.	Found
HO$(CH_2)_3$I	99–100	20	1.5480	19.37	19.65	3.80	3.81	I, 68.23	I, 68.10
HO$(CH_2)_3$SCN	143–144	14	1.4688	41.00	40.97	6.03	6.10	N, 11.96	N, 11.66
F$(CH_2)_4$I	53–54	13	1.4940					I, 63.78	I, 64.08
F$(CH_2)_4$CN	72	10	1.3963					F, 18.81	F, 18.6
F$(CH_2)_4$SCN	100–101	13	1.4611	45.11	44.96	6.01	5.90	N, 10.52	N, 10.35

In view of the ready conversion of halides and sulphonates to fluorides by potassium fluoride (16, 17), a representative nitrate was examined under conditions similar to those reported. On heating hexyl nitrate at 110° for eight hours with potassium fluoride in diethylene glycol, low yields (10–15%) of hexyl fluoride were obtained. From this preliminary observation, it seems unlikely that nitrates will be used extensively in the preparation of aliphatic fluorides.

In compounds containing both sulphonate and halogen groups, the former have been shown to be preferentially replaced relative to the latter (17), as for example in the conversion of 4-chlorobutyl methanesulphonate by potassium thiocyanate to 4-chlorobutyl thiocyanate in 67% yield. This was not possible with ω-haloalkyl nitrates; under the conditions necessary to replace the nitrate grouping, the halogen was also replaced.

From limited observations, alkyl nitrites proved to be useless as alternatives to nitrates in the replacement reactions described above. Under conditions similar to those used for converting hexyl nitrate to hexyl iodide, hexyl nitrite formed *n*-hexanol.

The preliminary results presented in this paper indicate that alkyl nitrates are of potential value as synthetic intermediates, while not offering any particular advantages over the well-known alkyl halides and sulphonates. It is hoped to examine the cleavage of nitrates in more complex molecules in order to assess the versatility and scope of the reaction.

EXPERIMENTAL[3]

(*a*) *Preparation of Intermediates*

Trimethylene iodohydrin.—Trimethylene chlorohydrin (20 gm., 0.21 mole), sodium iodide (63 gm., 0.42 mole), and anhydrous acetone (200 ml.) were heated under reflux for 13 hr. Most of the acetone was removed by distillation. After the mixture had been cooled and diluted with water, the product was extracted with ether. The extract was dried over anhydrous sodium sulphate. The ether was removed, and the residue on fractional distillation from freshly prepared silver crystals yielded trimethylene iodohydrin (19.7 gm., 50%) of b.p. 105° at 25 mm. and n_D^{25} 1.5480.

4-Fluorobutyl bromide, 4-fluorobutyl iodide, and 6-fluorohexyl bromide have been described elsewhere (16).

4-Chlorobutyl iodide was prepared from 1,4-dichlorobutane using sodium iodide in acetone (1).

(*b*) *Preparation of Nitrates*

The four methods summarized in Table I are represented by the following examples.

Method I: Benzyl nitrate.—Benzyl chloride (80 gm., 0.63 mole) was added over a period of 10 min. to silver nitrate (130 gm., 0.76 mole) in anhydrous acetonitrile (150 ml.). The mixture was then heated under reflux for 50 min. The silver chloride was removed by filtration and washed with a small quantity of acetonitrile. After removal of the acetonitrile at a temperature of less than 90°, the residue on distillation yielded benzyl nitrate (68.4 gm., 70%).

Method II: n-Hexyl nitrate.—*n*-Hexyl bromide (84.5 gm., 0.51 mole) was slowly added to a solution of silver nitrate (116 gm., 0.68 mole) in anhydrous acetonitrile (110 ml.) and the resultant mixture was allowed to stand at room temperature for 15 hr. After removal of the silver bromide by filtration, the mixture was heated under reflux for one hour. The solution was cooled and filtered, and then diluted with water (250 ml.). The crude nitrate was extracted with ether and the extract dried over anhydrous sodium sulphate. After removal of the ether, *n*-hexyl nitrate (62.5 gm., 83%) was obtained as a colorless liquid.

Method III: 4-Fluorobutyl nitrate.—4-Fluorobutyl iodide (47.0 gm., 0.23 mole) was slowly added to silver nitrate (42.5 gm., 0.25 mole) in anhydrous acetonitrile (60 ml.) with external cooling provided by an ice bath. The mixture was allowed to stand at room temperature for 19 hr., was filtered, and then the solvent removed. The residue on distillation yielded 4-fluorobutyl nitrate (23.8 gm., 75%).

[3]*Physical constants and analytical data are listed in Tables I and III.*

Method IV: n-Butyl nitrate.—Concentrated sulphuric acid (76.8 ml., specific gravity 1.84, 95% by weight) was slowly added at a temperature of less than 10° to a mixture of urea (2.5 gm.) and concentrated nitric acid (76.8 ml., 1.2 moles, specific gravity 1.42, 70% by weight). The resultant solution was cooled to 0° in an ice–HCl bath, and *n*-butyl alcohol (44.4 gm., 0.60 mole) was added with vigorous stirring at the rate of about 1 ml. per min. When the addition was complete, the mixture was stirred for a further 15 min. and then diluted with water. The nitrate layer was washed three times with 10% aqueous potassium carbonate and then with water. After it was dried over anhydrous sodium sulphate, distillation yielded *n*-butyl nitrate (52.8 gm., 74%) as a colorless, pleasant-smelling liquid.

(*c*) *Cleavages of Nitrates*

The following examples are representative of the cleavages of nitrates.

n-Hexyl iodide.—*n*-Hexyl nitrate (8.0 gm., 0.054 mole), sodium iodide (16.2 gm., 0.108 mole), and anhydrous acetone (40 ml.) were heated under reflux for 27 hr. The solvent was removed by distillation below 58°, and the residue was diluted with water (100 ml.) and extracted with ether. The extracts were washed successively with water, aqueous sodium thiosulphate, and water. They were then dried over anhydrous sodium sulphate and the ether was removed; the residue on distillation yielded *n*-hexyl iodide (9.7 gm., 84%), b.p. 60–63° at 12 mm., n_D^{25} 1.4894.

n-Heptanonitrile.—*n*-Hexyl nitrate (10.0 gm., 0.068 mole), sodium cyanide (3.4 gm., 0.070 mole), and ethylene glycol (20 ml.) were stirred at reflux temperature for two hours. The reddish-brown reaction mixture was diluted with water (200 ml.) and extracted with ether. The extracts were washed successively with 4 *N* hydrochloric acid (to remove traces of the isonitrile), aqueous sodium bicarbonate, and water, and dried over anhydrous magnesium sulphate. The ether was removed, and the residue on distillation yielded *n*-heptanonitrile (5.8 gm., 77%), b.p. 98° at 39 mm., n_D^{25} 1.4135.

4-Fluorobutyl thiocyanate.—4-Fluorobutyl nitrate (6.0 gm., 0.044 mole), potassium thiocyanate (12.8 gm., 0.132 mole), and 95% ethanol (50 ml.) were heated under reflux for 12 hr. The mixture was cooled, diluted with water (200 ml.), and extracted with ether. The extracts were washed with saturated calcium chloride and with water, and then dried over anhydrous sodium sulphate. After removal of the ether, the residue on distillation yielded 4-fluorobutyl thiocyanate (3.3 gm., 57%), a colorless, vile-smelling liquid.

Benzyl bromide.—A mixture of benzyl nitrate (6.0 gm., 0.039 mole), sodium bromide (12.1 gm., 0.117 mole), and anhydrous acetone (125 ml.) was heated under reflux with stirring for 26 hr. After the usual isolation procedure (removal of acetone, dilution with water, ether extraction, and drying), benzyl bromide (4.3 gm., 64%) was obtained as a colorless, lachrymatory liquid of b.p. 81–83° at 14 mm. and n_D^{25} 1.5690; Baker (2) reports b.p. 85° at 13 mm.

Benzyl mercaptan.—Benzyl nitrate (15.3 gm., 0.10 mole), thiourea (7.2 gm., 0.095 mole), and 95% ethanol (20 ml.) were heated under reflux for 4.5 hr. The cooled mixture was diluted with water (75 ml.) and the crude benzyl isothiouronium nitrate was collected by filtration. A small sample, recrystallized

from water, had m.p. 120–120.5°; Taylor (21) reports m.p. 118–119°. To the crude solid was added a solution of sodium hydroxide (8.0 gm., 0.20 mole) in water (80 ml.), and the mixture was heated under reflux for four hours. After it had been cooled and acidified with 3 *N* hydrochloric acid (75 ml.), the solution was extracted with ether. The extract was washed with aqueous sodium bicarbonate and with water, and dried over anhydrous sodium sulphate. After removal of the ether, the residue on distillation yielded benzyl mercaptan (3.8 gm., 32%) of b.p. 88–89° at 18 mm. and n_D^{25} 1.5723; Farlow and Signaigo (8) report b.p. 99° at 32 mm. and n_D^{25} 1.5729.

ACKNOWLEDGMENTS

The work described herein was carried out under contract (DRB X-24) with the Defence Research Board, to whom acknowledgment is made for financial assistance and for permission to publish this work. The authors wish also to express their indebtedness to the Research Council of Ontario for a scholarship for one of us (G. M. B.), and to Mr. Karlis Sketris for help in the preparations.

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THE REACTION OF ACTIVE NITROGEN WITH MERCURY DIETHYL[1]

By D. A. Armstrong[2] and C. A. Winkler

ABSTRACT

The main organic product of the reaction was hydrogen cyanide, the maximum yield of which was practically independent of temperature in the range 130° to 330°C., and appeared to correspond to about one-half the active nitrogen concentration present. Presumably the reactant or products, or both, caused deactivation of about one-half the active nitrogen. Small amounts of butane, propane, ethane, methane, propylene, ethylene, acetylene, and cyanogen were also found in the products.

INTRODUCTION

The results of a previous study with azomethane (1) indicated that the methyl radical – active nitrogen reaction is very fast and characterized by a low activation energy. The present investigation was made to determine whether the reactions of active nitrogen with metal alkyls might give useful information about active nitrogen – free radical reactions.

EXPERIMENTAL

The apparatus and analytical procedures were similar to those outlined in the earlier paper. The molecular nitrogen flow rate was 9.75×10^{-5} mole/sec. throughout, while the mercury diethyl flow was varied between 0.5×10^{-6} and 10^{-5} mole/sec. Pressures in the reaction vessel were 0.90 to 0.95 mm.

RESULTS AND DISCUSSION

The reaction gave a lilac-colored flame at all flow rates and temperatures, and caused the temperature to increase in the uncovered reaction vessel from 53°C. (active nitrogen alone) to about 130°C.

Hydrogen cyanide was the main organic product of the reaction. Mass spectrometric analysis of the fraction taken from a LeRoy still (2) at −155°C. showed the presence of small quantities of propane, ethane, ethylene, propylene, and acetylene. Similar analysis of two samples of non-condensable gas from the reaction at 350°C. indicated methane to the extent of about 5% of the HCN, and hydrogen roughly equivalent to the HCN. Small quantities of cyanogen and butane were also detected in the reaction products but were not estimated quantitatively. Polymer formation in the reaction vessel was negligible at all temperatures.

The relations between the product yields and mercury diethyl flow rate are shown in Fig. 1. The carbon balances were generally poor; they fell as low as

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Contribution from the Physical Chemistry Laboratory, McGill University, Montreal, Quebec, with financial assistance from the National Research Council and the Consolidated Mining and Smelting Company, Trail, British Columbia.
[2]*Holder of National Research Council Studentship, 1953–54, and Cominco Fellowship, 1954–55.*

73% and rarely exceeded 90%. The difficulty appeared to be in obtaining satisfactory recovery of the unreacted mercury diethyl.

As in previous papers, the results may be discussed on the basis that atomic nitrogen is the main reactive species in active nitrogen.

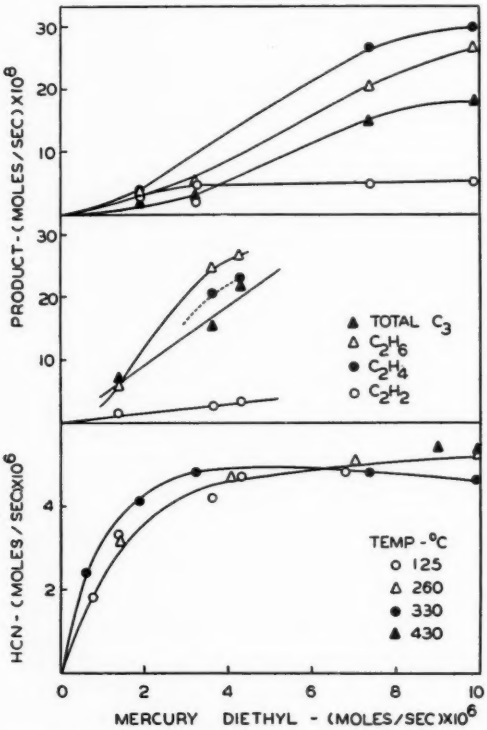

FIG. 1. Relation of product yields to mercury diethyl flow rate. Top curves at 330°C. Middle curves at 125°C.

The maximum production of hydrogen cyanide from mercury diethyl was roughly one-half the maximum amount obtained from ethylene in the same apparatus under comparable conditions. It would seem, therefore, that extensive recombination of nitrogen atoms was promoted in the mercury diethyl reaction. Moreover, the relative temperature independence of the maximum hydrogen cyanide yield indicates that the activation energies for the reactions leading to hydrogen cyanide production and to recombination were approximately the same, and probably quite low.

Recombination of nitrogen atoms was probably catalyzed to some extent by mercury atoms, since traces of mercury nitride were indicated by formation

of titratable base when water was added to the small amounts of residue that remained in the trap after distillation. Recombination could also result from the probable primary reaction

$$N + Hg(C_2H_5)_2 \rightarrow C_2H_5 + N.Hg.C_2H_5,$$

followed by

$$N + N.HgC_2H_5 \rightarrow N_2 + Hg + C_2H_5,$$

and possibly, to some extent, by

$$\begin{aligned} N + N.HgC_2H_5 &\rightarrow N_2 + Hg + C_2H_4 + H \\ &\rightarrow N_2 + Hg + C_2H_2 + H_2 + H \end{aligned}$$

since ethylene and acetylene were found in the products.

The presence of only small quantities of butane in the products indicates that ethyl radicals, like methyl radicals, (1), react rapidly with nitrogen atoms, probably by one or more of the following reactions:

$$\begin{aligned} N + C_2H_5 &\rightarrow HCN + CH_3 + H \\ &\rightarrow HCN + CH_2 + H_2 \\ &\rightarrow \ CN + CH_3 + H_2. \end{aligned}$$

Free radical and hydrogen atom reactions would lead to the small amounts of various secondary products obtained.

Owing to the marked deactivation of active nitrogen observed in the present study, it would seem that metal alkyls are not a particularly satisfactory source of radicals for study of active nitrogen – free radical reactions.

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THE ULTRAVIOLET ABSORPTION SPECTRA OF METHYL-1,2-BENZANTHRACENES[1]

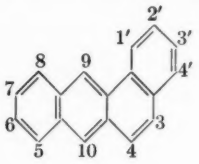
By C. Sandorfy[2] and R. Norman Jones

ABSTRACT

The ultraviolet absorption spectra of 1,2-benzanthracene, all twelve monomethyl derivatives, and six dimethyl derivatives have been measured (*a*) at room temperature in *n*-heptane solution, (*b*) at −100°C. in *n*-pentane solution. An analysis of the band envelopes indicates that most of the absorption between 33,000 and 25,000 cm.$^{-1}$ arises from two series of overlapping bands. The members of each series are spaced at intervals of approximately 1400 cm.$^{-1}$. The spacing between the two band series and their relative intensities are dependent on the nature and position of the alkyl substituents. Absorption between 40,000 and 33,000 cm.$^{-1}$ can be treated in a similar manner. Other fine structure is also observed. It is considered most probable that each of the overlapping series of bands is associated with a separate electronic excitation. The significance of these observations is considered in relation to the theoretical treatments of the energy levels of 1,2-benzanthracene as developed by Klevens and Platt and by Moffitt.

INTRODUCTION

The ultraviolet absorption spectra of 1,2-benzanthracene (I) and of a number of its alkyl derivatives were measured several years ago by Mayneord and



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Roe (23) and by Jones (11), using photographic recording techniques with Hilger Spekker photometers. Similar studies have since been carried out by Badger, Pearce, and Pettit (1) and by Friedel and Orchin (8) using photoelectric spectrophotometers. These investigations were made in ethanol solution at room temperature. The later work revealed little additional structure in the absorption bands, and it is evident that instrumental insufficiencies were not a serious factor in limiting the resolution of the vibrational fine structure.

In the present investigation, the spectra of 1,2-benzanthracene, all twelve monomethyl derivatives, and six dimethyl derivatives have been studied both at room temperature in *n*-heptane solution, and at −100°C. in *n*-pentane solution. Considerably more structure is revealed in the low temperature spectra, and an analysis of the bands has provided additional information about the energy levels of the 1,2-benzanthracene ring system.

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Contribution from the Division of Pure Chemistry, National Research Council, Ottawa, Canada. Presented in part at a Symposium on Molecular Structure and Spectroscopy, The Ohio State University, June 1952, and at a meeting of The Photoelectric Spectrometry Group, Imperial College, London, England, June 1954. Issued as N.R.C. No. 3968.
[2]*National Research Council Postdoctorate Fellow. Present address: Department of Chemistry, University of Montreal, Montreal, Que.*

EXPERIMENTAL

The measurements in *n*-heptane were carried out with a Cary spectrophotometer (Model 11 M) operated in the conventional manner. Quartz cells of 1 cm. path length were used, and the cell lengths were calibrated with potassium chromate solution (9). The hydrocarbon (2–3 mgm.) was weighed on a microbalance, dissolved in approximately 10 ml. of *n*-heptane, and the solution weighed to 0.1 mgm. From this primary solution, secondary and tertiary solutions of 1/10 and 1/100 of the initial concentration were prepared gravimetrically. These manipulations were carried out in a constant temperature room at 22°C. and the molarities computed on the basis of a density of 0.684 for all solutions. The *n*-heptane was purified by chromatographic adsorption on silica gel. The maximal extinction coefficients were checked by measurements on duplicate solutions. A mean variation of $\pm 1\%$ was observed in separate determinations. The spectrometer wavelength scale was calibrated against a mercury arc spectrum and neon and argon emission spectra. To facilitate the band analysis, the spectra were subsequently replotted on a linear scale of wave number.

The spectra in *n*-pentane solution were measured on the Cary spectrophotometer using the low temperature cell described by Jones and Keir (13). In these measurements intensities are less accurate because of the errors in the reproducibility of the solvent correction curve and the correction factor for change of the specific gravity of the solution with temperature. These errors

TABLE I

SOURCE AND MELTING POINT CHARACTERIZATION OF 1,2-BENZANTHRACENE AND DERIVATIVES

Compound	M.P.	Source*
1,2-Benzanthracene	158.5–160.5	1
1′-Methyl-1,2-benzanthracene	137.6–138.5	3
2′-Methyl-1,2-benzanthracene	150.6–151.4	3
3′-Methyl-1,2-benzanthracene	163.3–164.0	3
4′-Methyl-1,2-benzanthracene	196.0–197.0	3
3-Methyl-1,2-benzanthracene	155.8–156.4	3
4-Methyl-1,2-benzanthracene	126.9–127.4	3
5-Methyl-1,2-benzanthracene	159.4–159.6	3
6-Methyl-1,2-benzanthracene	152.3–152.8	3
7-Methyl-1,2-benzanthracene	185.1–185.4	3
8-Methyl-1,2-benzanthracene	118.0–118.4	3
9-Methyl-1,2-benzanthracene	139.0–139.4	3
10-Methyl-1,2-benzanthracene	140.0–140.5	3
1′,10-Dimethyl-1,2-benzanthracene	124 –125	1[a]
2′,6-Dimethyl-1,2-benzanthracene	163 –164	2[b]
2′,7-Dimethyl-1,2-benzanthracene	240.2–240.5	2[b]
3′,6-Dimethyl-1,2-benzanthracene	186.0–186.5	2[b]
3′,7-Dimethyl-1,2-benzanthracene	189 –190	2[b]
9,10-Dimethyl-1,2-benzanthracene	122.7–123.4	1
1′,9-Methylene-1,2-benzanthracene	121.5–122.0	1[c]

*1. *L. F. Fieser, Harvard University.*
2. *J. W. Cook, Chester Beatty Research Inst., London, England.*
3. *M. S. Newman, The Ohio State University.*
[a]*See Reference 7.*
[b]*See Reference 4.*
[c]*See Reference 6.*

cannot be evaluated precisely but are probably of the order of $\pm 5\%$ at the absorption maxima. The melting points and sources of the compounds are listed in Table I. The values reported for the positions of the absorption maxima are accurate to ± 20 cm.$^{-1}$ on sharp bands, but the uncertainty increases as the bands become more diffuse.

RESULTS

The curves reproduced in this paper have been selected to illustrate points which arise in the discussion. A separate bulletin (14) will be published which will contain the complete collection of curves, together with tables of the positions of the absorption maxima for the *n*-pentane solutions at $-100°$, and tables of the intensities and positions of the maxima for the *n*-heptane solutions at room temperature.

In ethanol solution at room temperature, 1,2-benzanthracene exhibited 12 absorption maxima between 43,000 and 25,000 cm.$^{-1}$. In an earlier publication (11) we labelled these bands *A–I*, *I'*, *J*, *K* as shown in Fig. 1. Intensity con-

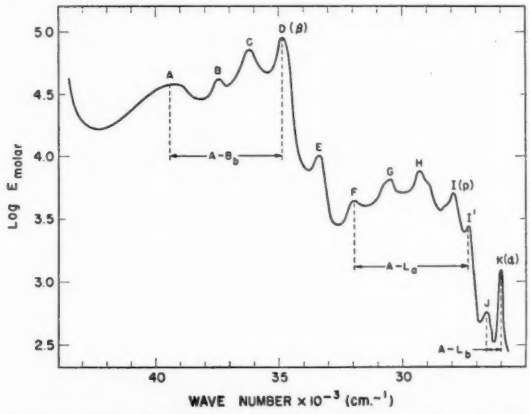


FIG. 1. Ultraviolet absorption spectrum of 1,2-benzanthracene in ethanol solution at room temperature. The nomenclature systems used by Clar (3), Jones (11), and Klevens and Platt (18) are indicated.

siderations suggested that the *A–D*, *F–I'*, and *J–K* bands probably constituted three separate groups. Klevens and Platt (18) have assigned these groups of bands to transitions from the ground state to three different electronic energy levels. These they designate B_b, L_a, and L_b in their system of nomenclature, which is based on a molecular orbital treatment of a free electron moving around the perimeter of the molecule. Clar (3) has identified our bands *D*, *I*, and *K* with β, *p*, and α in his nomenclature system, which is based on an empirical treatment of the band shifts with changes in "Anellierung". Other systems of nomenclature are used by Coulson (5) and by Moffitt (24).

Room Temperature Spectra in n-Heptane

The spectrum of 1,2-benzanthracene in *n*-heptane at room temperature is shown in Fig. 2. On the introduction of methyl substituents changes occur in

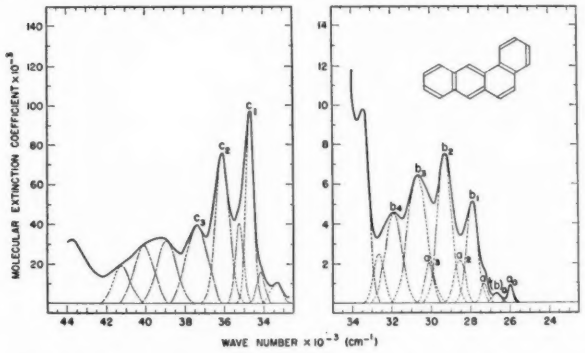


FIG. 2. Ultraviolet absorption spectrum of 1,2-benzanthracene in *n*-heptane solution at room temperature.

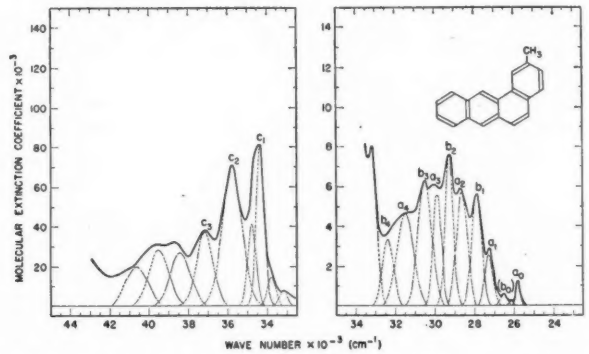


FIG. 3. Ultraviolet absorption spectrum of 2′-methyl-1,2-benzanthracene in *n*-heptane solution at room temperature.

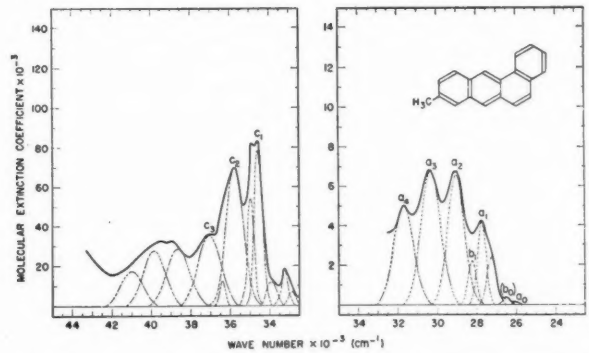


FIG. 4. Ultraviolet absorption spectrum of 6-methyl-1,2-benzanthracene in *n*-heptane solution at room temperature.

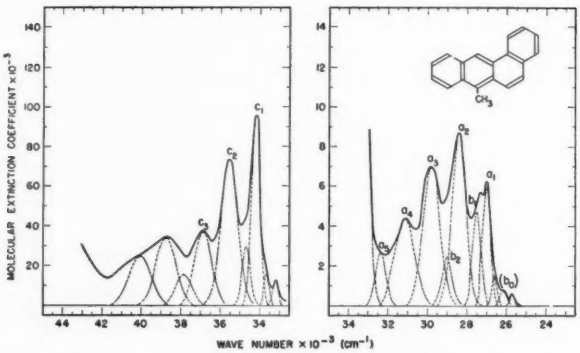


FIG. 5. Ultraviolet absorption spectrum of 10-methyl-1,2-benzanthracene in *n*-heptane solution at room temperature.

the band contours. The curves for the 2′-methyl, 6-methyl, and 10-methyl derivatives, shown in Figs. 3–5, are typical examples. The 2′-methyl and 10-methyl spectra have been chosen to illustrate the more highly and less highly inflected types of band envelope in the 33,000–25,000 cm.$^{-1}$ region. Neither of these two is highly inflected at higher frequencies, but additional structure is exhibited near 35,000 cm.$^{-1}$ in the spectrum of the 6-methyl compound shown in Fig. 5.

In a first attempt to investigate this structure systematically, the band envelopes were analyzed in terms of a series of Gauss curves.

This method of curve analysis has been employed by earlier investigators (2, 19, 16, 17). It is assumed that the envelope can be represented by a series of functions of the form

$$[1] \qquad \epsilon = \epsilon_{max} \exp[-\{(\nu-\nu_0)/h\}^2]$$

where the constants h, ϵ_{max}, and ν_0, indicated in Fig. 6, can be chosen to conform with a selected band.

In applying the method, the absorption peaks of most symmetrical appearance are first fitted by appropriate Gauss curves. The difference between these Gauss curves and the observed band envelope is next plotted and a second series of Gauss curves constructed to fit the most symmetrical peaks of the difference curve. These are in turn subtracted out and the process repeated as often as necessary. In selecting the most suitable Gauss functions, qualitative consideration is given to the displacement effects of overlap on the positions of the band maxima. These were established from analytical studies similar to those made by Vandenbelt and Henrich (29).

Examples of such curve analyses are shown in Figs. 2–5. The complete series of curves for the monomethyl-1,2-benzanthracenes were analyzed in this fashion and in spite of the differences in the complexity of the band contours, it was observed that in the majority of cases approximately the same number of Gauss curves were required, namely 10 or 11 for the 33,000–25,000

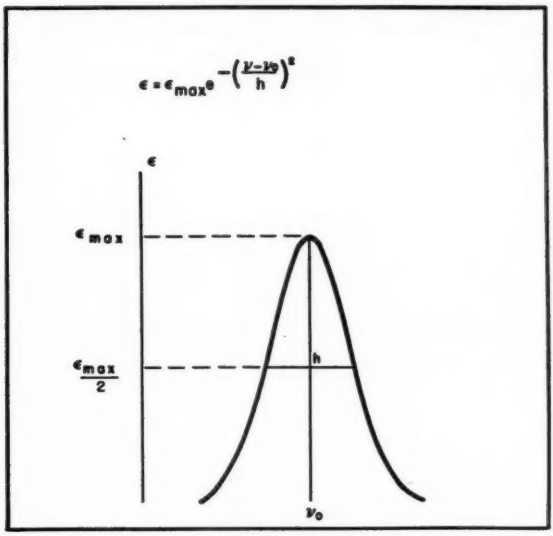


FIG. 6. The Gauss function.

cm.$^{-1}$ region and about eight for the 40,000–33,000 cm.$^{-1}$ region. Since there are arbitrary elements in the selection of the parameters, these do not represent unique analyses of the band envelopes. Nevertheless a comparison of the spacing and intensity of the Gauss curves indicates that between 33,000 and 25,000 cm.$^{-1}$ the spectra consist essentially of two overlapping systems of bands; these we have designated the *a* and *b* band series. The members of each series are spaced at intervals of approximately 1400 cm.$^{-1}$. In the individual compounds these overlapping series differ in their relative intensity and phase relationship. When both are of comparable intensity and the phase separation is great the band envelope appears complex (Fig. 3) but if one series is of predominating intensity or the phase difference is small the contour is simpler (Fig. 5). Between 38,000 and 33,000 cm.$^{-1}$ there is one well-defined set of bands, the *c* series, also with approximately 1400 cm.$^{-1}$ spacing, and possibly also a second one.

Low Temperature Spectra in n-Pentane

In the low temperature spectra these band series can usually be recognized on inspection. The low temperature spectra of 1,2-benzanthracene and of the 2′-methyl, 6-methyl, and 10-methyl derivatives are shown in Figs. 7–10, together with diagrams of the proposed schematic breakdown into band series. Similar diagrams for all the compounds are included in Reference 14 together with tables of the frequencies of the individual spacings in the band series.

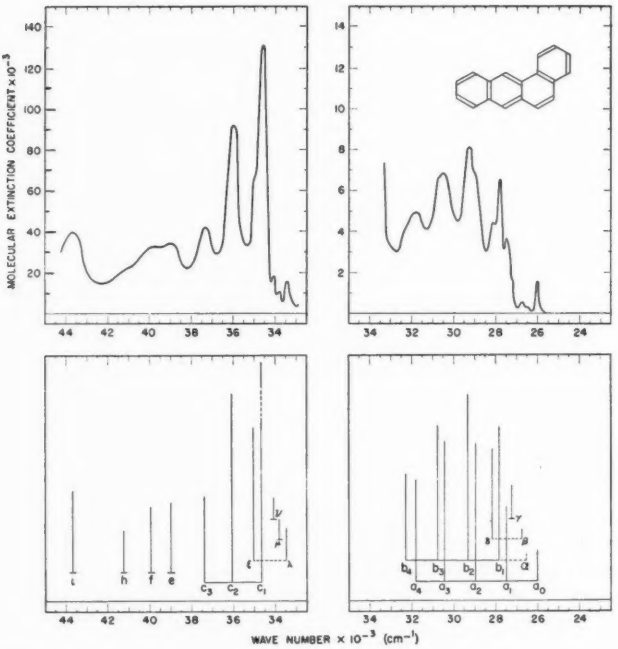


FIG. 7. Ultraviolet absorption spectrum of 1,2-benzanthracene in *n*-pentane solution at −100°C.

In addition to these three main series of bands, several other bands are observed in most of the spectra. These can be considered in three groups: (i) seven bands (α–η) overlapping the *a* and *b* series; (ii) nine bands (λ–τ) overlapping the *c* series; (iii) five bands (*e*–*i*) between 44,000 and 38,000 cm.$^{-1}$. Although this complete set of 21 bands is not observed in the spectrum of any single compound, collectively it accounts for the observed maxima and significant inflections in all the compounds and on this basis the generalized schematic diagram shown in Fig. 11 is proposed.

Comparison of the spacings between the "Greek letter" bands suggests that they probably include at least one additional series in the 38,000–33,000 cm.$^{-1}$ region. This is composed of bands λ, ξ, and ρ, and will be treated as a tentative *d* series in the discussion which follows. In many of the compounds spacings in the range between 1200 and 1500 cm.$^{-1}$ are commonly observed between certain of the Greek letter bands as indicated by the dotted lines in Fig. 11. This figure has been constructed in a manner to emphasize these relationships, but these bands are often diffuse and the similarity of the spacings may be in part fortuitous. For detailed numerical analyses see Table I of Reference 14.

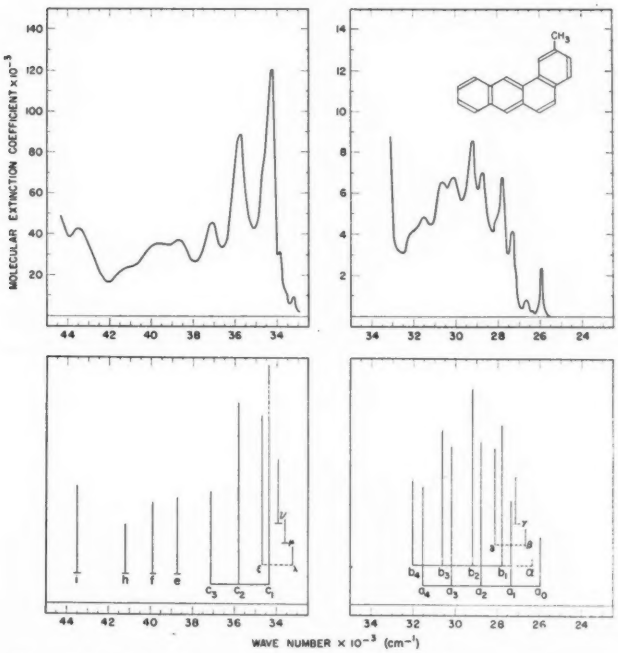


FIG. 8. Ultraviolet absorption spectrum of 2′-methyl-1,2-benzanthracene in *n*-pentane solution at −100°C.

In the schematic diagrams, the height of the line corresponds to the total intensity of the band envelope, and does not make allowance for contributions from overlap with neighboring bands. From this point of view the Gauss curves provide a truer picture of the intensity relationships between the band series, and the best analysis of the spectra would result from Gauss analysis of the low temperature curves. The process is tedious, however, and has not yet been carried out. In some cases it has been observed that the Gauss analysis successfully predicts bands that are not apparent on visual observation of the room temperature spectra. Thus the bands near 34,600, 32,700, 29,000, and 26,500 cm.$^{-1}$ in the Gauss analysis of the spectrum of 10-methyl-1,2-benzanthracene shown in Fig. 5 are resolved as bands **o**, a_5, b_2, and γ in the low temperature spectrum (Fig. 10).

The a and b Series

In most of the spectra, the middle members of these series show the highest intensities. The two series are most sharply differentiated in the spectra of the 2′-methyl, 3-methyl, 4-methyl, 7-methyl, 2′,7-dimethyl, and 3′,7-dimethyl compounds. The separation tends to become less clear at the higher frequencies where the *b* band may be reduced to an inflection on the side of the *a* band, as

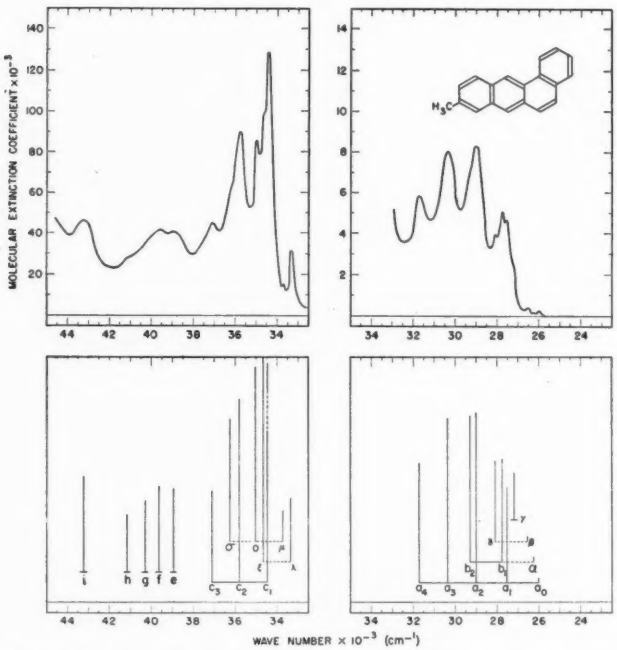


FIG. 9. Ultraviolet absorption spectrum of 6-methyl-1,2-benzanthracene in *n*-pentane solution at −100°C.

is the case for the 5-methyl, 8-methyl, 10-methyl, and 2′,6-dimethyl spectra. The *a* band series can usually be followed out to a_4, and in some compounds (5-methyl, 8-methyl, 9-methyl, 10-methyl, and 1′,10-dimethyl) band a_5 can also be decerned as an inflection on the leading edge of band λ.

Considerable interest is attached to the band of lowest frequency, which we have identified as a_0. This has theoretical implications that are considered in the discussion section.

The spacing of the a_0 band from the a_1 band lies in the range 1425±65 cm.$^{-1}$ in all except the 10-methyl compound. In the 10-methyl spectrum, the band of lowest frequency is at 25,720 cm.$^{-1}$, spaced 1130 cm.$^{-1}$ below the band at 26,850 cm.$^{-1}$ which we must assign to a_1 by virtue of its relationship to the higher members of the *a* series. The 25,720 cm.$^{-1}$ band is consistent with a β assignment and is spaced 1380 cm.$^{-1}$ below the inflection at 27,100 cm.$^{-1}$ which is assigned to δ (Fig. 10). The difficulty associated with the assignment of the a_0 band in 10-methyl-1,2-benzanthracene is important theoretically and it cannot be due solely to the presence of the 10-methyl substituent since in the 1′,10-dimethyl compound the band of lowest frequency (a_0) is at 25,530 cm.$^{-1}$, spaced 1360 cm.$^{-1}$ below a_1. From this we must conclude either that band a_0 is absent from the spectrum of the 10-methyl compound, or else that the a_1–a_0 spacing of 1425±65 cm.$^{-1}$ is fortuitous in its seeming relationship to the

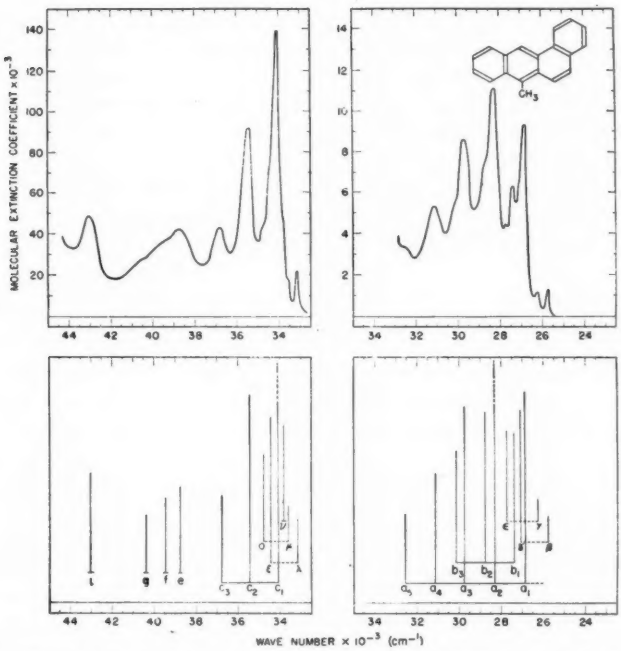


FIG. 10. Ultraviolet absorption spectrum of 10-methyl-1,2-benzanthracene in *n*-pentane solution at −100°C.

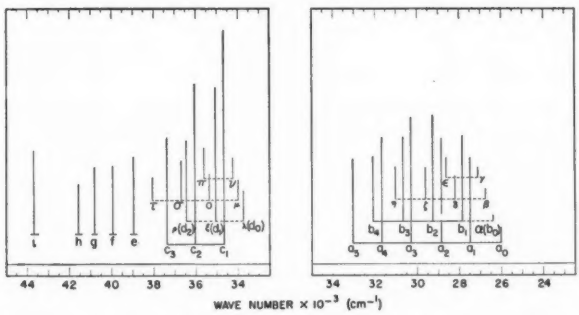


FIG. 11. Schematic diagram of proposed absorption band systems generalized from the spectra of 1,2-benzanthracene and all methyl derivatives.

1408 ± 90 cm.$^{-1}$ spacing between the higher members of the a series in all the other 18 derivatives.

The first member of the b series that can be clearly recognized in all the compounds is located between a_1 and a_2, and is defined as b_1. A weak band (α) is observed near $b_1 - 1400$ cm.$^{-1}$ in the spectrum of 1,2-benzanthracene and in the 2′-methyl, 4-methyl, 6-methyl, and 2′,7-dimethyl compounds; the b_1–β

spacing is also approximately 1400 cm.$^{-1}$ in the 1′-methyl, 3-methyl, and 7-methyl compounds. These might suggest that there is a weak b_0 member of the series, but no band assignable to b_0 can be observed in the spectra of the other compounds. The mean spacings for the b_4, b_3, b_2, b_1 series in all the compounds is 1423±85 cm.$^{-1}$, but the difference from the a series spacing of 1408±90 cm.$^{-1}$ is not considered significant.

With diminishing temperature, both the a and b series sharpen, but the temperature effect is usually much more pronounced on the a series than on the b series, as is shown for the 4-methyl compound in Fig. 12.

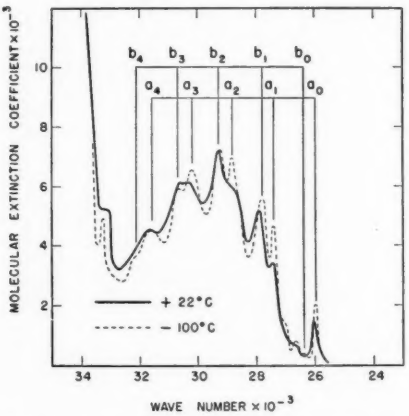


FIG. 12. Ultraviolet absorption spectrum of 4-methyl-1,2-benzanthracene in n-pentane solution illustrating differential temperature effects on the a and b band series.

The α–η Bands

The letters $\alpha \ldots \eta$ are assigned to weak bands or inflections that overlap the a and b series. These bands show positional analogies in the various compounds from which it might be inferred that the bands carrying the same letter are probably associated with similar excitation processes in the different compounds; there is however no real evidence for this.

In several of the compounds it has been noted above that α might be associated with the b series. In all 11 compounds where δ is observed, the δ–β spacing falls in the range 1383±150 cm.$^{-1}$. In the 8-methyl compound two additional inflections are also observed with spacings η–ζ, ζ–δ, and δ–β of 1400, 1260, and 1250 cm.$^{-1}$. Some of the other compounds show changes of contour on the sides of the a_2 and a_3 bands which suggest that bands analogous to η and ζ might be detected under more favorable experimental conditions (e.g. lower temperatures). These bands probably result from combination of the a series excitations with other vibrational modes.

The bands ϵ and γ are observed in four compounds and band γ alone in an additional six. These are weaker and more diffuse than the η, ζ, δ, β series, but probably arise from a similar type of excitation process.

The c Series

Between 38,000 and 33,000 cm.$^{-1}$ the spectrum is dominated by the *c* series, and in all compounds three members of this series are observed with spacings of 1373±105 cm.$^{-1}$. This is considered a significantly smaller spacing than that noted above for the *a* and *b* series. Bands *e* and *f* are observed in the region where c_4 and c_5 would be expected. In the 4-methyl, 5-methyl, and 9-methyl compounds the positions and intensities of *e* and *f* are not inconsistent with c_4 and c_5 assignments, but in the other compounds neither the positions nor the intensities of bands *e* . . . *h* can be reconciled with the extension of the *c* series beyond c_3.

The λ–τ Bands

The fine structure that appears between a_5 and c_3 shows a similarity to the fine structure of the α . . . η group, but there is a suggestion that bands λ, ξ, and ρ which have a mean spacing of 1346 cm.$^{-1}$±140 cm.$^{-1}$ may constitute a *d* series. They are, however, too strongly overlapped by the *c* series to establish this with certainty.

The *c* series is much more temperature sensitive than the underlying bands, and this is particularly noticeable on c_1. Attempts have been made in earlier work to associate the position of the peak of the absorption envelope in this region ("band *D*" of Fig. 1) with the relative carcinogenicity of these compounds (11). We see from the present series of measurements that this peak is composite, and the position of this maximum is more sensitive to temperature change than other parts of the absorption envelope. In a number of cases (such as the 6-methyl compound, shown in Fig. 13), the contour of the band envelope

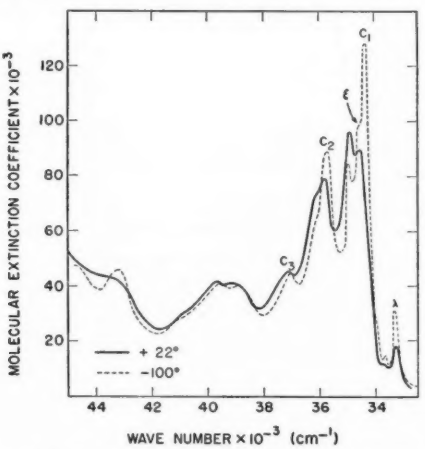


FIG. 13. Ultraviolet absorption spectrum of 6-methyl-1,2-benzanthracene in *n*-pentane solution illustrating strong temperature effect in the neighborhood of band C_1.

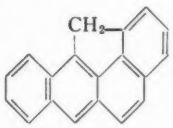
suggests that at room temperature band ξ predominates and that the relative intensities of the ξ and c_1 peaks are reversed on cooling.

Absorption above 38,000 cm.$^{-1}$

In all the compounds there is a well-defined band near 43,000 cm.$^{-1}$ (band *i*), and this constitutes the upper limit of our range of measurement. The group of three or four bands (*h* . . . *e*) between 42,000 and 38,000 cm.$^{-1}$ is usually very diffuse.

The Spectrum of 1′,9-Methylene-1,2-benzanthracene

It has been noted previously (12) that the spectra of 1′,9-methylene-1,2-benzanthracene (II) and its 10-methyl derivative differ significantly from the spectra of the simple alkyl 1,2-benzanthracenes. The low temperature spectrum



II

of II is shown in Fig. 14. The main differences are noted between 36,000 and 34,000 cm.$^{-1}$ and between 28,000 and 25,000 cm.$^{-1}$. The region below 33,000

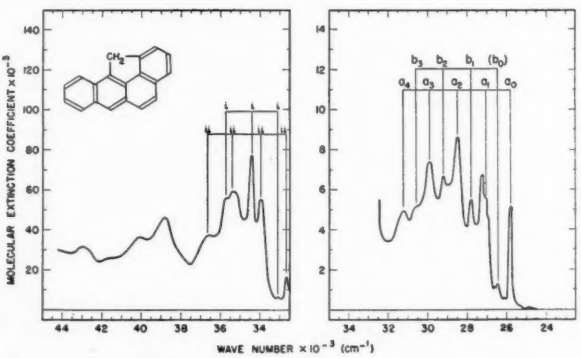


FIG. 14. Ultraviolet absorption spectrum of 1′,9-methylene-1,2-benzanthracene in *n*-pentane solution at −100°C.

cm.$^{-1}$ consists of two well-defined series of bands, the stronger of which we can identify with our *a* series, and the weaker with our *b* series. The *a* series seems more pronounced than in the simple alkyl derivatives. The spectrum between 38,000 and 32,000 cm.$^{-1}$ can also be resolved into two series of bands (*i* and *ii*). It is not clear what relationship these two series bear to the *c* and (tentative) *d* series of the methyl derivatives.

DISCUSSION

The principle features of the near ultraviolet spectra of aromatic hydrocarbons have been discussed by Coulson (5) and by Klevens and Platt (18, 25, 26). These authors developed molecular orbital treatments of the electronic energy levels of these molecules, which Moffitt (24) has refined and extended.

In benzene, the three lowest singlet electronic band systems begin near 38,000, 48,050, and 57,000 cm.$^{-1}$. These are associated with excitation from the ground state (^1A) to the L_b, L_a, and B_b excited states of Platt. They correspond to the α, p, and β bands of Clar.* The first two of these electronic transitions are forbidden by symmetry and appear only in combination with non totally symmetrical vibrations.

The near ultraviolet and visible spectra of the acene polynuclear aromatic hydrocarbons also exhibit three broadly distinguishable band systems, and these are generally considered to be related to the three electronic states of benzene described above. The band of lowest frequency (Clar's α band) is polarized along the longer in-plane axis, as is required for the ^1A–^1L_b transition. The next band system (Clar's p band) is polarized along the shorter in-plane axis, while the third band series (Clar's β) is again long-axis polarized. The p-system was first shown by Clar to be very sensitive to linear "Anellierung" and to shift rapidly to lower frequency in the series naphthalene → anthracene → naphthacene → pentacene. Clar's α band is much less affected by linear "Anellierung". In anthracene and naphthacene it is submerged beneath the stronger and more rapidly moving p-system (p. 249 of Ref. 3). Clar's strong β band increases in intensity with linear "Anellierung" and shifts to lower frequency at about the same rate as the α band.

In the angular acene hydrocarbons the same three groups of bands are identified. Clar's α and β bands remain in approximately the same positions as in the linear "anellierte" isomers, but the p band is displaced to higher frequency. Platt has described these bands in terms of "long field" and "round field" structures (26), and has shown in a few cases that, as the two principle in-plane axes become more similar, the p band system shifts to higher frequency.

The above description has been concerned only with the electronic transitions, and the quantum mechanical treatments of Coulson, Platt, and Moffitt do not take notice of the vibrational structure. This vibrational structure is associated mainly with 0–0, 0–1, 0–2 . . . transitions in accordance with selection rules developed by Herzberg, Sponer, and Teller (10, 28). This vibrational structure has been investigated more thoroughly for naphthalene than for the more complex polynuclear aromatic hydrocarbons (15, 20, 21, 22, 27). The spacing of approximately 1400 cm.$^{-1}$ to which we attach particular importance in our analyses of the 1,2-benzanthracene spectra is common to many polynuclear aromatic hydrocarbons and shows up prominently in anthracene (12).

If we disregard the minor bands, we have in 1,2-benzanthracene the three well-established a, b, and c series which are all progressions of a 1400 cm.$^{-1}$ vibration. Our a series might be identified with Platt's A–L_b transition and our b series with Platt's A–L_a transition. In both the L_b and L_a states the equilibrium positions of the atoms must be significantly different from those in the ground state, as the most intense bands are about the middle of the progres-

**For purely descriptive purposes we prefer to use Clar's nomenclature since it avoids implications concerning the type of electronic transition involved.*

sion. No "hot" bands arising from excited vibrational levels of the ground state would appear to be present since we see no bands that weaken on cooling.

This interpretation would imply that the *a* and *b* band series are associated with excitation to closely lying but distinct electronic states, rather than to two different vibrations and their overtones in the same excited state. Our experimental observations do not allow us to distinguish with certainty between these alternative interpretations, but there are two arguments that favor the hypothesis of separate electronic states. If only one electronic state were involved we would formulate the *a* series as

$$a_n = a_0 + 1400\, n \qquad (n = 0, 1, 2, 3, 4, 5) \tag{2}$$

and the *b* series

$$b_n = a_0 + \nu_b + 1400\, n \tag{3}$$

where ν_b is a vibrational term that combines with the $1400\, n$ term. A comparison of the frequencies of the individual *a* and *b* bands in the complete series of compounds (Table II) shows that the spacing between the two series $(b_n - a_n)$ varies over a range from 774 cm.$^{-1}$ for the 2′,7-dimethyl compound to 200 cm.$^{-1}$ for the 6-methyl compound, and it seems unlikely that a combination term such as ν_b of equation [3] would behave in this manner. The inverse of this argument has been used by McConnell and McClure (21) to support their contention that part of the fine structure in the naphthalene spectrum involves only one electronic state. The marked difference in the temperature effect on the *a* and *b* band series is also more readily explained in terms of two separate electronic states, as this type of behavior would hardly

TABLE II

MEAN SEPARATION $(b_n - a_n)$ BETWEEN BANDS OF THE *b* SERIES AND *a* SERIES IN THE ULTRAVIOLET ABSORPTION SPECTRA OF 1,2-BENZANTHRACENES

Compound	$(b_n - a_n)$, cm.$^{-1}$
1,2-Benzanthracene	346
1′-Methyl-1,2-benzanthracene	502
2′-Methyl-1,2-benzanthracene	502
3′-Methyl-1,2-benzanthracene	235
4′-Methyl-1,2-benzanthracene	210
3-Methyl-1,2-benzanthracene	674
4-Methyl-1,2-benzanthracene	424
5-Methyl-1,2-benzanthracene	363
6-Methyl-1,2-benzanthracene	200
7-Methyl-1,2-benzanthracene	610
8-Methyl-1,2-benzanthracene	287
9-Methyl-1,2-benzanthracene	365
10-Methyl-1,2-benzanthracene	497
1′,10-Dimethyl-1,2-benzanthracene	290
2′,6-Dimethyl-1,2-benzanthracene	412
2′,7-Dimethyl-1,2-benzanthracene	774
3′,6-Dimethyl-1,2-benzanthracene	300
3′,7-Dimethyl-1,2-benzanthracene	390
9,10-Dimethyl-1,2-benzanthracene	—
1′,9-Methylene-1,2-benzanthracene	690

be expected for two vibrations of closely lying frequency in the same electronic level.

These observations would also be compatible with the assumption of the excitation of one of the series from an excited level lying very near the ground state. Such a postulation of two closely lying initial states, however, would seem unlikely on chemical grounds for a molecule of this type.

In the 38,000–33,000 cm.$^{-1}$ region we can associate the c band series with the A–B_b electronic transition of Platt, and there is no reason to question the assignment of the intense c_1 band to the 0–0 vibrational transition, since we can detect no band near c_1-1400 cm.$^{-1}$. In the B_b state the equilibrium positions of the atoms would be similar to those in the ground state if the 0–0 band is the most intense. If we accept the more problematical identification of bands λ, ξ, and ρ with a d series we are presented with a problem of interpretation very similar to that of the a and b series discussed above, and we would then require four electronic transitions to account for the observed spectrum below 38,000 cm.$^{-1}$; this is one more than is provided by the theoretical treatments of Platt and of Moffitt. We might note in this connection that neither of these authors made any assignment for our band λ which we would now regard as the 0–0 vibrational transition associated with a postulated fourth electronic state. In the above discussion we have omitted consideration of the minor bands μ, ν, o, π, σ, τ, but these probably arise from other combinations of vibrational terms.

Above 38,000 cm.$^{-1}$ these studies do not add greatly to our knowledge of these spectra. They suggest only that the absorption above 38,000 cm.$^{-1}$ is not directly related to that below, and we may therefore need to invoke one or more additional electronic states to account for bands e, f, g, h, and i. Band i has been associated by Platt with his ^1A–^1C_b transition.

We have noted in a previous section that in 10-methyl-1,2-benzanthracene there are difficulties in assigning the a_0 band. If we accept this as evidence that the numerical relationship of the a_0 band to the higher members of the a series is fortuitous in all the other compounds, we have to conclude that a_0 forms a separate band system. This is contradicted however by the general observation that in those compounds in which a_0 is prominent the same holds true also for the other bands assigned to the a series. This can be noted by comparison of the spectra of the 2′-methyl and 1′,9-methylene compounds on the one hand with that of the 6-methyl on the other (Figs. 8, 9, 14).

In view of the high intensity of all of this absorption we must presume that it arises from singlet–singlet transitions, and McClure (20) has identified the first and second singlet–triplet transitions of 1,2-benzanthracene with much weaker absorption near 16,500 and 35,950 cm.$^{-1}$.

CONCLUDING REMARKS

It will be of interest to determine whether or not the spectra of other types of polynuclear aromatic hydrocarbons can be treated in a similar fashion. In this connection we would stress the value of examining an extensive set of simple alkyl derivatives. The diffuseness of the bands, even at low temperatures,

makes it difficult to locate the positions of the maxima with sufficient precision to establish the validity of such series from observations on a single compound. Alkylation appears to have a definite effect in displacing the series relative to each other, and it is only when similar series of bands can be identified in the spectra of a number of alkyl derivatives that we consider these conclusions to have significance. Similar studies are at present being made on the methyl-3,4-benzphenanthrenes and will be reported in due course.

It may be noted in conclusion that attempts have been made to correlate the bathochromic shifts produced by methylation with the conjugating power defined in terms of the self-polarizability of 1,2-benzanthracene at the position of substitution (1). More recently the electron density in the highest occupied orbital has been employed (24*a*). The correlations between these calculated shifts and the observed shifts are often far from satisfactory. The observed shifts are determined from the maxima of the band envelopes; the present work emphasizes the complexity of these band envelopes and the sensitivity of their peak positions to extraneous influences. It is therefore not surprising that the agreement between theory and experiment is relatively poor.

ACKNOWLEDGMENTS

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We also wish to thank Mrs. M. A. MacKenzie and Mr. D. S. Keir for their assistance with the experimental measurements.

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THE PREPARATION AND PROPERTIES OF α-D-GLUCOPYRANOSE 1,2-(ETHYL ORTHOACETATE) TRIACETATE[1]

By R. U. Lemieux and J. D. T. Cipera[2]

ABSTRACT

Crystalline ethyl and propyl 1,2-orthoacetates of α-D-glucopyranose triacetate were prepared. Conclusions are drawn regarding the chemical properties and configurations of these compounds which are based on the conformation of the 1,2-cyclic carboxonium ion believed to be formed when the substances are treated with acetic acid.

Lemieux and Brice (10) prepared a crude sirupy α-D-glucopyranose 1,2-(methyl orthoacetate) triacetate by reaction of tetra-*O*-acetyl-β-D-glucopyranosyl chloride (I) with methanol in the presence of silver carbonate. We wish to report crystalline ethyl (III) and *n*-propyl 1,2-orthoacetates of α-D-glucopyranose triacetate obtained by reaction of the β-chloride (I) with the appropriate alcohol in the presence of dry pyridine. The orthoesters crystallized directly from the reaction mixture and are thus readily prepared. All efforts to obtain crystalline α-D-glucopyranose 1,2-(methyl orthoacetate) triacetate have failed.

The compound III in the presence of acids and bases reacted in the manner expected for orthoacetate structures (12). In view of the established properties of the β-chloride (I) (10) and related compounds (7), there could be little doubt that the substance possesses a 1,2-orthoacetate ring. This prediction was confirmed by deacetylation of III followed by methylation and hydrolysis of the product to form 3,4,6-trimethyl-D-glucose. It is noteworthy that these reactions provide a much easier preparation of the latter compound than was hitherto available (13).

The orthoester (III) had a half-life of 4.38 min. (polarimetric) when dissolved in 95% aqueous dioxane 0.0061 *N* with hydrochloric acid at 28°C. When the compound was dissolved in 99% acetic at 28°C. it was rapidly (1.75 min.) converted to 2,3,4,6-tetra-*O*-acetyl-α-D-glucose (V). However, in carefully dried acetic acid, β-D-glucopyranose pentaacetate (VI) was the main product. Thus, the behavior of the orthoester in acetic acid paralleled closely that of the β-chloride (I) in wet and dry acetic acid (10). When the orthoester (III) was dissolved in acetic acid containing varying amounts of water, the rotation of the reaction product increased with increasing amounts of water until the amount of water was about equimolar to the orthoester. Greater amounts of water resulted in reaction products with approximately the same rotation (see Table I). Thus, the orthoester reacted substantially quantitatively with the traces of water present in the acetic acid. This result strongly suggests that the orthoester (III) is dissociated in acetic acid to the cyclic carboxonium

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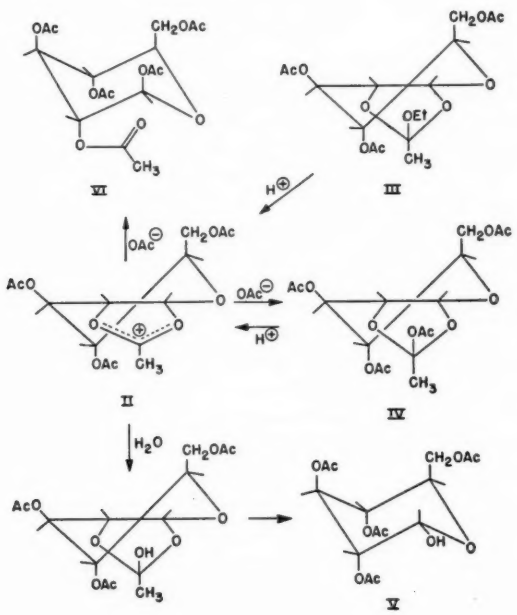
TABLE I

MAXIMUM ROTATION ACHIEVED IN THE REACTION OF α-D-GLUCOPYRANOSE 1,2-(ETHYL ORTHOACETATE) TRIACETATE (0.089 *M*) IN AQUEOUS ACETIC ACID

Concentration of water (*M*)[a]	Specific rotation
0	+51°[b]
0.041	77
0.062	99
0.19	103
0.53	107

[a] *See the experimental portion.*
[b] *The specific rotation of β-glucopyranose pentaacetate under these conditions was 5.5°.*

ion (II) through co-ordination of the acid with the ethoxyl group oxygen atom rather than by co-ordination with the central atom of the C_5–O–C_1–O–C–O–C_2 system as proposed by Pacsu (12, p. 103) for acid hydrolysis of cyclic sugar orthoesters. The result strongly infers this reaction route because of the stereochemical results of the hydrolysis and acetolysis reactions and the fact that the ion (II) can be expected to accept a nucleophilic reagent at the easily accessible 1,2-cyclic structure much more readily than at the highly hindered (because of the axial CH_2OAc group) rear side of the lactol carbon atom. Thus, the ability of the ion to search out mere traces of water in acetic acid becomes understandable. The 1,2-(acetyl orthoacetate) triacetate (IV) must have a



transient existence in these reactions. Furthermore, reaction by way of the ion (II) is highly attractive from energy considerations (7). The conformation of the ion (II) is based on the established conformation of six-membered rings fused 1,2-*cis* to planar five-membered ring (1, 4) and on the evidence provided by Lemieux and Brice (9) that the CH_2OAc group must be situated in close proximity to the anomeric center.

It has often been observed in the preparation of sugar 1,2-orthoesters that the degree of partial asymmetric synthesis is high since only one of the two possible diastereoisomers is obtained and this often in high yield. A consideration of a molecular model of the ion (II) leaves little doubt that the orthoester (III) is formed by approach of the nucleophilic reagent on the side of the positively charged center which is *trans* to the pyranose ring. The orthoester (III) must possess the α-D-configuration and has a much lower specific rotation, +31°, than has ethyl α-D-glucopyranoside tetraacetate, +132.1° (5). On the other hand, β-D-mannopyranose 1,2-(methyl orthoacetate) triacetate has a specific rotation, −26.6° (3), not greatly different from that of methyl β-D-mannopyranoside tetraacetate, −46.8° (3). Clearly, therefore, the difference in rotation cannot be attributed to contributions to rotation by the asymmetric center of the orthoester group. Instead, these data strongly suggest that conformation has an important effect on rotation. It is of interest to note in this respect that the rotation of the orthoester (III) is close in value to that measured for 1,2-(1-methylpentylidene)-α-D-glucopyranose triacetate, +24.7°, by Hurd and Holysz (6).

EXPERIMENTAL

β-D-*Glucopyranosyl Chloride Tetraacetate* (*I*)

The material used, m.p. 95–98°C., was prepared by the procedure of Lemieux and Brice (10) and was recrystallized once from ether–pentane.

α-D-*Glucopyranose 1,2-*(*Ethyl Orthoacetate*) *Triacetate* (*III*)

The chloride (I), 6 gm., was added to a mixture of 3 ml. dry pyridine in 15 ml. anhydrous ethanol. The compound (II) dissolved after the mixture was shaken at room temperature for 20 min. The mixture was left at −10°C. for 30 hr. and the crystalline product was collected. After two recrystallizations from ethanol, the yield was 3.96 gm. (61.5%), m.p. 97–97.5°C., $[\alpha]_D$ +31° (*c*, 1 in chloroform). These constants were not changed by further recrystallizations. Calc. for $C_{16}H_{24}O_{10}$: C, 51.1; H, 6.42%; saponification equiv., 125.4. Found: C, 50.3; H, 6.1%; saponification equiv., 125.5, 124.8. The half-time of reaction, determined polarimetrically, was about 14.5 min. when 100 mgm. of the chloride (I) was dissolved in 5 ml. of 9:1 ethanol–pyridine at room temperature.

The results given in Table I for the reactions of the ethyl orthoester (III) in acetic acid solution were obtained by dissolving 100 mgm. of the compound in 3 ml. of the acetic acid. The dry acetic acid was prepared by reacting glacial acetic acid with acetic anhydride in the presence of sulphuric acid followed by distillation in a dry atmosphere. The solutions of water in acetic

acid were prepared gravimetrically. Since the specific rotation of the β-D-glucopyranose pentaacetate in this solvent was +5.5° and the reaction of the ethyl orthoester in the solvent gave a rise in rotation to +51°C., it was apparent that either the acetic acid was not altogether dry or else some water was absorbed in the several transfers necessary to prepare the solution and to follow the rotation. It was clear that the latter was the case since substantially pure β-D-glucose pentaacetate, m.p. 129–132°C. (pure, m.p. 132.5–133.5°C. after one recrystallization from ethanol), was formed when the ethyl orthoester (III) was dissolved in the solvent kept in a dry atmosphere. When the orthoester (III), 100 mgm., was dissolved in 6 ml. of 99% acetic acid, the product was soluble and mutarotated in water. Recrystallization of the material from ether–pentane gave 2,3,4,6-tetra-*O*-acetyl-α-D-glucose (10), m.p. 97.5–98.7°C., $[\alpha]_D$ +122° (chloroform).

3,4,6-Tri-O-methyl-D-glucose

The ethyl orthoester (III), 1.1 gm., was deacetylated at room temperature with methanolic ammonia. The sirup, which remained after solvent removal, was dissolved in 2 ml. dry methanol and the solution was methylated with 6 ml. methyl iodide and 6 gm. silver oxide added in portions in the usual manner (2). The product was remethylated in the same manner except that only 0.5 ml. of methanol was used. The product was extracted with hexane to yield a hexane-soluble sirup which gave an observed rotation +10° in 5 ml. dioxane. The rotation rapidly rose to +24° on the addition of 0.25 ml. of 0.1 *N* hydrochloric acid. The orthoester ring therefore survived the methylation. The solution was evaporated to dryness and the residue was heated at 100°C. for two hours with 10 ml. 0.1 *N* hydrochloric acid to complete hydrolysis. Paper chromatography showed the solution to contain a substance with the R_f value in the range expected for a trimethylglucose along with a small amount of dimethylglucose. The dimethyl derivative was removed by partition chromatography using Celite to support the aqueous phase and *n*-butanol saturated with water as the developing phase (11) to yield 360 mgm. of trimethylglucose. This substance must be 3,4,6-trimethyl-D-glucose, since it was rapidly and completely converted by periodate to only one substance which after alkaline hydrolysis moved on a paper chromatogram in the manner expected for 2,3,5-tri-*O*-methylarabinose (8).

α-D-Glucopyranose 1,2-(n-Propyl Orthoacetate) Triacetate

This substance was obtained in 62% crude yield, m.p. 60–69°, under the conditions described above for the preparation of the ethyl orthoester. Two recrystallizations from ethanol gave apparently pure material, m.p. 92–94.5°C., $[\alpha]_D$ +39.5° (*c*, 1 in chloroform). The substance possessed the properties expected for an orthoester structure and must be the compound indicated.

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A NEW SYNTHESIS OF DL-γ-HYDROXY-ORNITHINE[1,2]

By Guy Talbot, Roger Gaudry, and Louis Berlinguet

ABSTRACT

A convenient synthesis of DL-hydroxy-ornithine is described. Starting from diethyl allylmalonate, it involves treatment with sulphuryl chloride followed by hydrolysis and distillation to give a 90% yield of 2,5-dichloro-4-valerolactone. Condensation of this with two equivalents of potassium phthalimide in dimethylformamide gives a quantitative yield of crude 2,5-diphthalimido-4-valerolactone. This lactone is converted quantitatively by acid hydrolysis to DL-γ-hydroxy-ornithine, isolated as the dihydrochloride of the corresponding 2,5-diamino-4-valerolactone. The over-all yield calculated from allyl chloride is 80%.

INTRODUCTION

2,5-Diamino-4-hydroxyvaleric acid (hydroxy-ornithine), a "non-natural" amino acid, was first synthesized in 1916 by Hammarsten (8), starting from allylhippuric acid. Other syntheses, developed by Traube, Johow, and Tepohl (13) in 1923, involved condensation between epichlorhydrin and diethyl malonate. In 1926, Tomita and Fukagawa (11) condensed 1-chloro-2-hydroxy-3-phthalimidopropane with diethyl phthalimidomalonate and in 1935, Tomita and Nakashima (12) reported on similar compounds. An attempt to synthesize hydroxy-ornithine from histidine by Langenbeck and Hutschenreuter (9) in 1929 has proved to be unsuccessful. Finally, Dey (3), in 1937, published a synthesis in which 1,2-epoxy-3-phthalimidopropane was condensed with diethyl malonate.

However, these various condensations led to extremely low yields of hydroxy-ornithine and consequently are not suitable for the preparation of substantial quantities of this amino acid. The need for a readily available intermediate thus became obvious.

The 2,5-dichloro- or 2,5-dibromo-valerolactones, which can be readily obtained (5), were first considered as possible starting materials. However, treatment of these lactones with ammonia favored cyclization to hydroxy-proline (5).

It was therefore decided to investigate the condensation of these 2,5-dihalogenated-4-valerolactones with potassium phthalimide.

Diethyl allylmalonate (III) was prepared in a 91% yield by condensation of allyl chloride (I) and diethyl malonate (II). Treatment of diethyl allylmalonate (III) with sulphuryl chloride or addition and substitution of bromine to the unsaturated free acid (IV) in chloroform, followed in both cases by acid hydrolysis and vacuum distillation, gave respectively a 90% yield of the 2,5-dichloro-4-valerolactone (V) and a 73% yield of the dibromo derivative (VI) (based on

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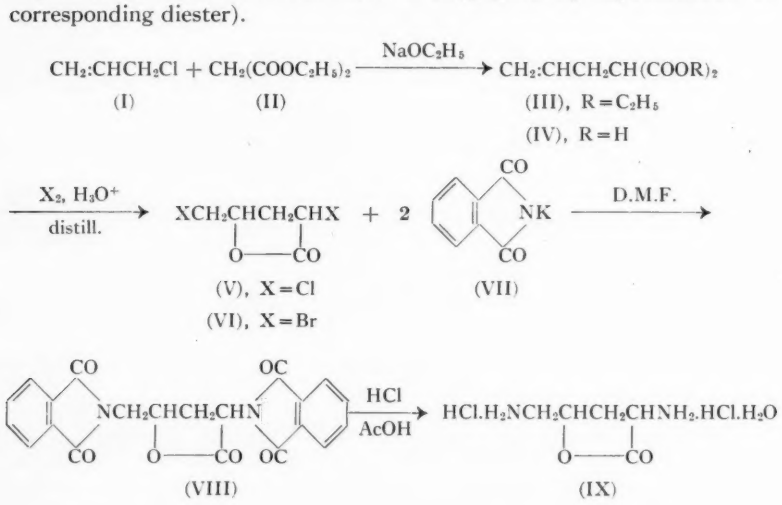
allylmalonic acid, itself obtainable in 82% yield by saponification of the corresponding diester).



The next step involved condensation of the dihalogenated lactones with two equivalents of potassium phthalimide (VII). Dimethylformamide (D.M.F.) was successfully used as a solvent for this reaction while other solvents like toluene or xylene (7) did not lead to a homogeneous product. In this manner, the two lactones led to a quantitative yield of crude 2,5-diphthalimido-4-valerolactone (VIII) which is virtually insoluble and which was best purified with little lost by treatment with activated charcoal in a large volume of glacial acetic acid.

The hydrolysis of the 2,5-diphthalimido-4-valerolactone (VIII) with a mixture of glacial acetic acid and concentrated hydrochloric acid gave a nearly quantitative yield of hydroxy-ornithine isolated as 2,5-diamino-4-valerolactone dihydrochloride monohydrate (IX).

The over-all yield of hydroxy-ornithine through the dichlorolactone amounted to 80% based on allyl chloride.

EXPERIMENTAL*

Diethyl Allylmalonate (III)

Using the method of Conrad and Bischoff (2), 153 gm. of allyl chloride (I) and 641 gm. of diethyl malonate (II) were condensed to give diethyl allylmalonate (III). Yield: 364 gm. (91%), b.p. 71–73° (1.5 mm.), n_D^{20}: 1.430. (Lit.: b.p. 93° (6 mm.) (4), n_D: 1.433 (6) or n_D^{20}: 1.430 (7).)

2,5-Dichloro-4-valerolactone (V)

Diethyl allylmalonate (III) (169.3 gm.) was treated with sulphuryl chloride (243 gm.), then hydrolyzed and vacuum distilled to give 2,5-dichloro-4-

**Melting points are uncorrected.*

valerolactone (V) as described by Gaudry and Godin (5). Yield: 129.1 gm. (90.5%), b.p. 118–121° (2 mm.), n_D^{20}: 1.495. (Lit.: b.p. 159–161° (13 mm.) (10), $n_D^{24.6}$: 1.496 (1).) Anal. Calc. for $C_5H_6O_2Cl_2$: Cl, 42.0. Found: Cl, 41.6.

Allylmalonic Acid (IV)

Saponification of 100 gm. of diethyl allylmalonate (III) by sodium hydroxide, followed by acidification, gave allylmalonic acid (IV). Yield: 58.8 gm. (82%), m.p. 103°. (Lit.: m.p. 103° (2).)

2,5-Dibromo-4-valerolactone (VI)

Allylmalonic acid (IV) (58.8 gm.) was treated with bromine (163 gm.) as described by Gaudry and Godin (5). The yield of 2,5-dibromo-4-valerolactone (VI) was 83.3 gm. (73%), b.p. 156–157° (4 mm.), n_D^{20}: 1.557. (Lit.: b.p. 150–151° (3 mm.), n_D^{20}: 1.555 (7).) Anal. Calc. for $C_5H_6O_2Br_2$: Br, 62.0. Found: Br, 62.1.

2,5-Diphthalimido-4-valerolactone (VIII)

2,5-Dichloro-4-valerolactone (V) (106.9 gm., 0.63 mole) was added dropwise, at room temperature, to a mechanically stirred suspension of potassium phthalimide (VII) (262 gm., 1.41 moles) in dimethylformamide (800 ml.). The mixture was then heated to about 100° for six hours. The liquid was slowly poured into four liters of water with vigorous stirring, the cold suspension filtered, and the residue washed thoroughly with water–ethanol mixture (4:1) and dried at 105° for several hours. The amorphous material thus obtained was sufficiently pure for use in the next step. Yield of crude product: 252 gm. Recrystallization from a large volume of glacial acetic acid gave crystals, m.p. 263°. (Lit.: m.p. 260° (3).) Anal. Calc. for $C_{21}H_{14}N_2O_6$: N, 7.18. Found: N, 7.24.

2,5-Diamino-4-valerolactone Dihydrochloride Monohydrate (IX)

A mixture of glacial acetic acid (350 ml.), concentrated hydrochloric acid (700 ml.), and 2,5-diphthalimido-4-valerolactone (VIII) (70.0 gm., 0.18 mole) was heated under reflux for 24 hr. The rather insoluble compound dissolved gradually as the hydrolysis proceeded. The filtrate was evaporated to dryness under reduced pressure after the phthalic acid had been removed from the cold solution. The residue was dissolved in water and the solution was decolorized with Norit, concentrated to a small volume, and precipitated by the addition of ethanol. Recrystallization from water–ethanol mixture gave the monohydrate of the 2,5-diamino-4-valerolactone dihydrochloride (IX). Yield: 38.8 gm. (98%), m.p. 239°. (Lit.: m.p. 239–240° (13).) Anal. Calc. for $C_5H_{10}O_2N_2.2HCl.H_2O$: N, 12.68; Cl, 32.05. Found: N, 12.68; Cl, 31.80.

The dihydrochloride when filtered through a column of a strongly basic resin (Permutit S-1) apparently gave the monohydrochloride, which could not be isolated. However, a chloride determination on an aliquot from the eluate gave a figure roughly equivalent to one half of the total chloride content of the dihydrochloride. The monopicrate, obtained by treating the eluate with one equivalent of picric acid, had a sharp melting point of 180° instead of 185–190° as reported by Hammarsten (8).

The 2,5-diamino-4-valerolactone, being a weak base, migrated toward the cathode when submitted to paper electrophoresis in a buffer solution of pH 8.6. The 2,5-diamino-4-valerolactone had a R_f value of about 0.24 on circular chromatograms in 80% pyridine – 20% water system, while in phenol saturated with water the R_f value for a one-dimensional chromatogram was around 0.10.

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THE POTENTIOMETRIC METHOD FOR THE DETERMINATION OF ALUMINUM ON A SEMIMICRO SCALE[1]

By J. R. McCallum[2]

ABSTRACT

The potentiometric method for the determination of aluminum proposed by Treadwell and Bernasconi has been modified for use on a semimicro scale and applied successfully to the analysis of pulp and paper ash. Samples containing as little as one milligram of aluminum have been titrated with an accuracy of 0.003 milligrams or better.

INTRODUCTION

A description of a potentiometric method for the determination of aluminum by titration with sodium fluoride, using a ferri-ferrous half cell, first appeared in a paper by Treadwell and Bernasconi (32) in 1930. The technique described in this paper is essentially the same as the original method except that it has been revised in detail to enable the determination to be made on the semimicro scale.

There are no other references to the practical application of this method in the West-European or North-American literature, except in such review papers as those by Furman (12, 13) and in the textbook by Kolthoff and Furman (17). In Eastern Europe the technique has proved to be popular and valuable for analysis of samples containing 50 mgm. or more of aluminum oxide. For example, Stefanovskii and Svirenko (23) applied the method to silicates and other ores with much success. They found that the method was not of much value for ores giving an iron oxide precipitate four or five times heavier than the aluminum oxide present. Ivanov and Bezyaiko (16) adopted the method for the determination of aluminum in steel and found it very useful if a partial separation of the iron from the aluminum was performed before the titration. This technique could also be applied to the ores high in iron content. These latter authors also found the method to be useful in the analysis of bronze. Mannchen (19) used the method for the determination of aluminum in magnesium alloys, and Pollack (20) used it in connection with electron-type alloys.

The versatility of this titration is not limited to the determination of aluminum in the presence of iron for widely differing samples. Suitably modified it has been used with great success to determine fluorine, titrating with an aluminum salt (25, 26), ferric chloride (24), or cerous nitrate (21). Dubinkov and Tikhomirov (11) compared several methods of fluorine analysis and found that the potentiometric titration was accurate for the analysis of sample solutions containing 0.2 mgm. of fluorine per liter or more. Tarayan (27) titrated beryllium in the absence of aluminum and calcium in the absence of magnesium (28) while Ringbom and Merikanto (22) also found it possible to determine calcium in this way.

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Contribution from the Quebec North Shore Paper Company, Baie Comeau Mill, Baie Comeau, Que.
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The method has a very firm theoretical foundation due almost entirely to the monumental work of Brosset and co-workers in Stockholm (Refs. 2 to 8). Contributions to the knowledge of the fundamental chemistry of the ferri-ferrous half cell and of the fluorine complexes formed during this titration have also been made by such authors as Connick and Tsao (9), Dodgen and Rollefson (10), Low and Pryde (18), and Babko and Kleiner (1). These papers are for the most part written in English and are readily obtainable so that a discussion of this theory is not necessary here.

During certain studies on pulp and paper it became necessary to analyze rapidly small samples of ash for various cations including aluminum. Several methods were attempted but all except this potentiometric procedure were unsuitable. For example, the classical methods of separation are accurate enough for fairly large amounts of aluminum but on the semimicro scale errors of 20% are common. The colorimetric method (14) was useless because of the excessive amounts of iron present in our samples. Complexing with thioglycolic acid in this method is only possible in samples containing not more than 100 μgm. of iron. Similarly the separation of iron from aluminum by precipitation in the presence of thioglycolic acid as suggested by Hummel and Sandell (15) was found to be quite accurate for fairly large samples of aluminum, over 100 mgm., but gave large random errors when used for samples containing 1 to 30 mgm. of aluminum. The iron exchange method of Teicher and Gordon (30) was also found to be of no value for these small amounts of aluminum. Therefore our interest was directed toward this potentiometric method which promised both accuracy and speed.

APPARATUS

The apparatus required is that normally used for potentiometric work—a sensitive potentiometer connected with two electrodes, in this case a calomel reference electrode and a bright platinum indicating electrode. The electrodes are inserted into a 30-ml. titration vessel which is fitted with a five-port cover. Four of the ports in the cover are located around the rim while the fifth is in the center. Titration from a 25-ml. standard burette or a 5-ml. microburette is carried out through the center port while air is excluded from the vessel by the introduction of a rapid stream of an inactive gas, carbon dioxide or nitrogen, playing on the surface of the solution through a fourth port. The burettes are to be accurate within the limits set by the United States Bureau of Standards for 'A' class volumetric glassware. The fifth port is reserved for the introduction of chemicals as required and is normally kept closed during titration so that the inactive gas escapes from the vessel around the tip of the burette. Stirring during titration is accomplished by means of a magnetic stirrer using a small, glass-covered rod $\frac{1}{2}$ in. long and 1/16 in. in diameter. The potentiometer used in our laboratory is the "Polymetron Model 42 Precision pH Meter" which is accurate to 0.01 pH or one millivolt when used as a potentiometer.

PROCEDURE

The samples of pulp or paper are incinerated according to standard methods (29). The ash sample is then transferred to a weighed platinum crucible and weighed. It is wetted with distilled water to prevent spattering, and dissolved in 10 ml. of warm 1:1 HCl. The acid solution and washings from the platinum crucible are filtered through a No. 42 Whatman paper into a 100-ml. volumetric flask, the filter paper being washed with three or four small portions of warm 1:1 HCl, followed by distilled water until the flask is almost filled to the mark. When cool the flask is filled to the mark with distilled water and 20 ml. aliquots for the aluminum determination transferred to small beakers. These are evaporated to dryness under an infrared lamp to remove excess hydrochloric acid. The residue is redissolved in a few drops of 1:1 HCl and 2 ml. of distilled water. When re-solution is complete this sample is washed with 8 ml. of saturated NaCl solution into the titration vessel. Absolute ethyl alcohol, 10 ml., is then added to the titration vessel. This causes some precipitation of the salt which provides a reservoir of ions so that the total ion activity during the titration remains practically constant. The cover of the titration vessel is then clamped into position and the magnetic stirrer started. The glass and calomel electrodes of the precision pH meter are then inserted through two of the ports in the cover and the pH of the solution is carefully adjusted to about 3.5 using 1/10 *N* solutions of sodium hydroxide and hydrochloric acid as required (see Table II).

The glass electrode is removed from the system after being washed with saturated salt solution. The neutral gas stream is started and the burette placed in position for titration. The solution of a ferrous salt required to complete the half cell with the ferric ions already present is added to the sample in the form of two drops of a 20% solution of ferrous chloride. It is desirable to make up fresh 10-ml. lots of this solution every four hours on days that the titration is used because it oxidizes very rapidly in the presence of air. This is also the reason why air is excluded from the titration vessel. At this point the platinum indicating electrode is inserted into the titration vessel and the pH meter is converted to read in millivolts. When the system reaches equilibrium, as indicated by a steady potential reading, titration may proceed using a standard sodium fluoride solution of appropriate strength: $\frac{1}{5}$ *N* when the aliquot contains more than 20 mgm. of aluminum, 1/10 *N* for more dilute samples.

If the approximate aluminum content is known, the titration may begin with fairly large portions, say 1 ml., of sodium fluoride, the potential reading being noted after each addition. Between each addition care must be taken to ensure that equilibrium is reached; the formation of the aluminum–fluoride complexes is a slow reaction and as long as five minutes between each addition of titrant may be required. The use of automatic titrating apparatus may reduce the time required for titration; this technique has not been attempted in this laboratory. On approaching the end point, which is indicated by a very rapid change in potential, no more than 1/10 ml. of titrant should be added

at a time. The end point is taken to be the point of maximum rate of change of potential. This does not coincide precisely with the equivalence point but the error introduced by this aberration is too small to be of practical importance.

THE TITRATION CURVE

Fig. 1 is an example of the type of titration curve obtained by this method. When about one-third to one-half of the titrant has been added to the ash solution there is a small abrupt decrease in potential which always occurs to a greater or lesser extent during this titration. Teodorovich (31) attributes this to the semiquantitative formation of the AlF_2Cl complex. This small inflection

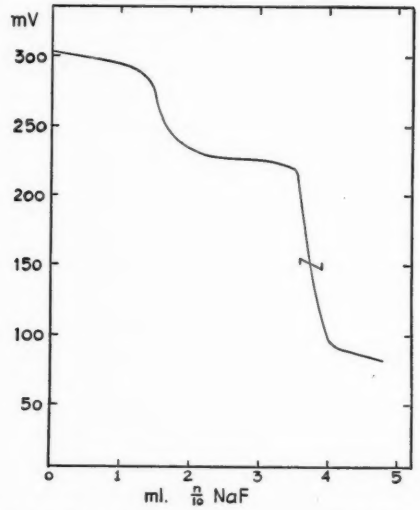

FIG. 1. A typical titration for aluminum in ash.

can be used as an indication of the approximate amount of sodium fluoride required in the titration and so the time taken per titration can be reduced. The time required for a titration is about 20 min.; the whole analysis for aluminum in pulp or paper ash can be done in about four hours, excluding the time required for ashing the paper.

INTERFERENCE

As calcium, magnesium, and beryllium can be determined by using this same potentiometric technique, some interference by them might be expected. However, it has been found in this laboratory and by other workers (17, 22) that the end point for aluminum is reached before complexing of the divalent cations with fluorine begins. If there are very large amounts of calcium and magnesium present in comparison to aluminum, the time taken for equilibrium to be reached after each addition of sodium fluoride is increased but there is no change in the final shape of the curve from the beginning of the titration to

the equivalence point. The tail of the curve after the equivalence point has been passed does depend on the amount of calcium and magnesium present and also on the amount of ferric iron in the sample. The curve tends to flatten out in the presence of calcium and magnesium, as shown in Fig. 1, and to remain flat until the equivalence point for the magnesium is reached. This has been used as the basis of a titration for aluminum and magnesium in the absence of calcium. Excessive amounts of ferric iron (more than three times the amount of aluminum present) decrease the potential change of the aluminum equivalence point and make the analysis unreliable (16, 23).

ACCURACY OF RESULTS

The results in Table I present some analyses of artificial ash mixtures containing known amounts of aluminum and iron. The sodium fluoride used for

TABLE I

TITRATION OF ARTIFICIAL ASH MIXTURES CONTAINING KNOWN AMOUNTS OF IRON AND ALUMINUM

Sample	Total aluminum present, mgm.	Total Fe^{+++} present, mgm.	Total aluminum found, mgm.	Error, %
1	0.085	1.037	0.084	−1.2
2	0.085	3.111	0.083	−2.4
3	0.085	5.185	0.081	−4.9
4	0.212	2.074	0.212	0
5	0.212	5.185	0.213	+0.5
6	1.571	0.620	1.571	0
7	1.571	1.861	1.571	0
8	2.510	1.861	2.514	+0.2
9	10.600	7.314	10.604	+0.05

these titrations was standardized against known solutions of both aluminum chloride and aluminum sulphate. In both cases it was found that 1 ml. of sodium fluoride was equivalent to 0.220 mgm. of aluminum for titrations 1 to 5, and 0.419 mgm. for the remainder. This table shows that for titrations involving less than one milligram of aluminum, quite high accuracy is possible in the presence of up to four times as much iron as aluminum; more iron than this introduces large errors because the rate of change of potential at the equivalence point becomes less as the amount of iron is increased and it is difficult, with the present equipment, to judge where the maximum rate of change occurs. With such small samples titration must be carried out with great care using a microburette.

The results in Table II show what happens when the pH during titration is varied. The results at 3.00 pH are a little high, those at 3.25 and 3.50 are quite acceptable. At 3.75 pH the potentiometer pointer was drifting quite erratically near the end point which made the readings very unreliable. At pH 4 there was no change in the potential reading even after the addition of 6 ml. of sodium fluoride, 3.88 ml. being the required amount. Hence titration at a pH between 3.25 and 3.50 is required.

TABLE II

Sample	Aluminum present, mgm.	pH at beginning of titration	Aluminum found, mgm.
1	1.624	3.00	1.661
2	1.624	3.25	1.623
3	1.762	3.50	1.762
4	1.624	3.75	1.561
5	1.624	4.00	0.000

SUMMARY

This method presents for the first time a technique whereby semimicro quantities of aluminum may be determined in the presence of relatively large amounts of iron with both accuracy and speed. The necessity for the separation of iron with its consequent risks of inaccuracy is eliminated. This renders the method suitable for routine analysis of very small samples. All previous applications of the potentiometric method to aluminum analysis have been on the macro scale.

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ANALYSIS FOR SMALL AMOUNTS OF CALCIUM, MAGNESIUM, BARIUM, AND SULPHATE USING PHTHALEIN PURPLE[1]

By J. R. McCallum[2]

ABSTRACT

For the determination of sulphate ion in samples containing 3 to 20 mgm., it was found that the standard precipitation techniques did not give sufficiently accurate results, and were time consuming. Reference to the literature showed that with certain modifications a complexometric method proposed by Schwarzenbach *et al.* for samples containing 20 to 50 mgm. of sulphate was most likely to give accurate results rapidly. In this method the sample is passed through a cation exchange column and washed with distilled water into a flask. This solution is boiled and precipitated with excess standard disodium ethylenediaminetetracetate in the presence of alcohol and ammonia using phthalein purple indicator. Provided that the details of procedure described in this paper are closely adhered to, accuracy is usually within two per cent. Calcium, magnesium, and barium may also be titrated directly using the phthalein purple indicator.

INTRODUCTION

During certain studies it became necessary to measure the amounts of sulphate present in samples of pulp and paper ash. It was required that the method chosen should measure quantities of sulphate weighing between 3 and 20 mgm. with an accuracy of three per cent or better. It should take no longer to perform than the standard gravimetric methods for larger samples.

Recourse to the literature produced references to several possible titrimetric methods. For example, Belcher and co-workers (2) precipitated and filtered as barium sulphate. This precipitate was then dissolved in excess standard ethylenediaminetetracetate and the solution back-titrated with a standard magnesium chloride solution to an eriochrome black (solochrome black) end point. Their results on samples containing 1 to 60 mgm. of sulphate are well within the limits mentioned above, but the method is tedious.

Munger and co-workers (3) precipitated the sulphate in slightly acid solution with a known excess of barium chloride. The mixture was boiled for a few minutes, cooled, and filtered. The filtrate was titrated to an eriochrome black end point. Their results with samples containing less than 20 p.p.m. of sulphate were not within the required limits. Sijderius (5, 6) followed much the same method and obtained results about 20% too low. He found it necessary to age the precipitate overnight as in the gravimetric methods and to filter before titration. Both Munger and Sijderius were troubled by the presence of carbonate and had to boil the original sample in a strongly acid medium before proceeding with the determination.

The main difficulty in these methods lies in the uncertainty of the eriochrome black end point. Munger (3) had to add a known amount of magnesium in order to make it sharp and clear. For this reason we became interested in a new indicator proposed in 1954 by Anderegg, Flaschka, Sallmann, and Schwar-

[1]*Manuscript received March 9, 1956.*
Contribution from the Quebec North Shore Paper Company, Baie Comeau Mill, Baie Comeau, Que.
[2]*Research chemist, Quebec North Shore Paper Company.*

zenbach (1, 4). These publications suggested that a particular complex organic acid indicator could be employed in a relatively simple procedure to determine the alkaline earth metals and that it might be similarly useful for the titration of sulphate in samples containing 20 to 50 mgm. of the ion. The present paper indicates specific conditions under which it may be so employed to determine sulphate when present in an aliquot at 3 to 20 mgm.

PROCEDURE

The method as described in this paper was developed specifically for the analysis of pulp and paper ash, but there is no reason to believe that it could not be applied to problems of a more general nature.

The sample of pulp or paper is ashed according to standard procedures (7). The ash so obtained is transferred to a platinum crucible or dish and weighed. It is wetted with a little distilled water and dissolved in 10 ml. of warm 1:1 hydrochloric acid. The acid solution and washings from the platinum crucible are filtered through a No. 42 Whatman paper into a 100-ml. volumetric flask, the filter paper being washed with three or four small portions of warm 1:1 hydrochloric acid, followed by distilled water until the flask is almost filled to the mark. When cool, the flask is filled to the mark with distilled water and 20 ml. aliquots for the sulphate determination are transferred to small beakers. These samples are evaporated to dryness under the infrared lamp to remove excess hydrochloric acid. The residues are redissolved in two or three drops of warm 1:1 hydrochloric acid and diluted with about 5 ml. of distilled water. These samples are then transferred to the reservoir of an ion exchange column together with the rinsings from the beaker.

The ion exchange column used was Amberlite IR-120(H) in a column 2 cm. in diameter and 25 cm. long. It was found that such a column could be used for 10 samples before regeneration with 3 *N* hydrochloric acid became necessary.

The sample is passed through the column at a rate of 5 ml. per min. and collected in a 250 ml. flask, followed by three 50 ml. portions of distilled water. The final volume of the sample should not be much more than 175 ml.

This solution is heated to boiling and treated with an excess of standard 0.05 *N* barium chloride solution, added from a calibrated microburette. The mixture is then boiled down to about 50 ml. Porous pot may be used at this stage to reduce bumping. The sample is then corked and aged for at least an hour, preferably two hours, at 60° C. or higher, after which it is allowed to cool to room temperature (cf. Table II).

The cool sample is made neutral to methyl red with sodium hydroxide solution; then an equal volume of ethyl alcohol is added to it. Absolute alcohol or any grade which is free of sulphate and alkaline earths may be used. From this point the solution absorbs carbon dioxide readily and the remainder of the analysis should be carried out with dispatch. Concentrated ammonia solution, 5 ml., and five to seven drops of the indicator mixture to be described later are added to the solution. Back titration with standard 0.05 *N* ethylenediaminetetracetate solution is begun immediately from a calibrated microburette and continued drop by drop until the sharp change from deep blue

through blue-green to yellow-green is complete. Almost invariably the color shifts back toward blue after the end point is reached for the first time; titration must be continued until a permanent yellow-green is established. This shift in color at end point becomes less and less noticeable as the aging time is increased. With overnight aging it is eliminated and it is suggested that, if convenient, the precipitate be aged overnight.

The above differs from the method of Schwarzenbach (4) in the concentration of several of the reagents, in the introduction of an aging period (which we have found essential to good results), and in the use of a microburette.

INDICATOR

The indicator for this titration was a mixture of 0.1 gm. phthalein purple,* 0.005 gm. methyl red, and 0.05 gm. dianil green† in 100 ml. of solution.

Schwarzenbach in his textbook (4) recommends the use of the phthalein purple by itself; the original paper (1) suggested a dye mixture similar to the above. We have tried both methods and recommend the use of the mixed indicator rather than phthalein purple alone because the mixture gives a much clearer end point. The shelf life of either indicator solution is about one week.

DETERMINATION OF THE ALKALINE EARTHS

For the titration of the alkaline earth metals the procedure is simple and direct, and our results confirm the recommendations of Schwarzenbach (4). The slightly acid solution, which must be free of ammonium salts, is adjusted to neutrality with sodium hydroxide (methyl red indicator) and made alkaline with 5 ml. of concentrated ammonia per 100 ml. of solution. Five to seven drops of phthalein purple or the mixed indicator are added to the sample giving a bright purple color. This mixture is titrated with a standard ethylenediaminetetracetate solution of strength appropriate to the sample being examined. The end point is a sharp change from the bright purple to a very pale pink or colorless condition. This requires but one drop of a 0.1 *N* ethylenediaminetetracetate solution. This method has been used by us to determine total water hardness and calcium, magnesium, and barium separately. The color change for magnesium is less sharp than for the others.

RESULTS

Table I gives the results for some analyses for sulphate on artificial ash mixtures. The "wash water" column indicates the amount used in the ion exchange step of the determination; the best results were obtained with 150 ml. wash. The last three samples also contained a little iron and silica; the exact quantities were not measured and so are not included in the table. It must be pointed out that to get results to agree as well as this it is necessary to follow all the details of the method as described above.

Table II presents two sets of results showing the effect of insufficient aging on the amount of sulphate found. Sufficient accuracy can be obtained after

Obtainable from J. & R. McJannet Regd., Montreal.
†No. 576 Allied Chemical & Dye Corporation.

TABLE I

TITRATIONS FOR SULPHATE

Titration number	Sample containing Al, mgm.	Ca, mgm.	Mg, mgm.	SO_4, mgm.	Wash water, cc.	SO_4 found, mgm.	Error, %
1[a]				7.16	125	7.17	−0.14
2			0.78	3.10	125	3.16	+1.94
3	0.95			5.20	125	5.05	−2.88
4	0.19	2.97	0.31	3.71	125	3.74	+0.81
5	0.29	4.45	0.45	5.57	75	5.23	−6.28
6	0.38	5.94	0.62	7.42	75	7.24	−2.43
7	0.12	2.97	0.79	7.33	75	7.06	−3.68
8	0.18	4.45	1.17	11.00	150	10.92	−0.73
9	0.24	5.94	1.56	14.66	150	14.74	+0.55
10	0.30	7.43	1.95	18.33	150	18.60	+1.47

[a] = *Ammonium sulphate solution.*

TABLE II

EFFECT OF DIFFERENT AGING TREATMENTS
150 cc. of wash water used during ion exchange step

Sample No.	Aging time	SO_4 present, mgm.	SO_4 found, mgm.	%
1	0	4.41	3.53	80
1	15 min.	4.41	4.02	91.3
1	30 min.	4.41	4.07	92.3
1	45 min.	4.41	4.37	99.2
1	1 hr.	4.41	4.39	99.5
1	18 hr.	4.41	4.39	99.5
2	20 min.	7.33	6.84	93.3
2	35 min.	7.33	7.08	96.6
2	50 min.	7.33	7.27	99.1
2	65 min.	7.33	7.34	100.1
2	12 hr.	7.33	7.32	99.9

45 min. of aging but the end point is very broad at this time and it is only by very careful approach to it that the accuracy reported may be obtained. At one hour the accuracy is good though the end point is still a little obscure. An aging period of at least one hour, preferably more than two hours, is recommended.

Table III gives some results for the analysis of solutions containing calcium, magnesium, and barium. The second result was obtained on a sample originally containing both calcium and magnesium which were separated by precipitation of the calcium as oxalate in the presence of acetic acid. The other calcium samples were prepared by dissolving calcium carbonate in a little hydrochloric acid and diluting the solution to a standard volume. Aliquots were taken for the titrimetric analysis and these were checked by gravimetric analysis of larger aliquots by the usual method of precipitation as oxalate. Samples 4 and 5 were standard solutions of magnesium sulphate, and 6 and 7 of barium chloride.

TABLE III

TITRATIONS OF CALCIUM, MAGNESIUM, AND BARIUM SOLUTIONS

Titration No.	Sample containing			Found		
	Ca, mgm.	Mg, mgm.	Ba, mgm.	Ca, mgm.	Mg, mgm.	Ba, mgm.
1	2.81			2.81		
2	3.21			3.24		
3	50.75			50.76		
4		0.41			0.41	
5		2.20			2.18	
6			3.49			3.50
7			7.00			6.98

ACKNOWLEDGMENT

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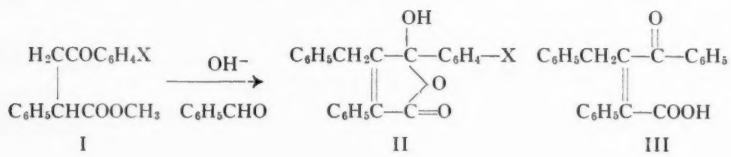
α-ARYL-β-AROYLPROPIONIC ACIDS AND THEIR CONDENSATION PRODUCTS WITH AROMATIC ALDEHYDES[1]

By C. F. H. Allen, T. J. Davis, D. W. Stewart, and J. A. VanAllan

ABSTRACT

It has been shown, by means of spectral analysis, that α-aryl-β-aroylpropionic acids exist in an open-chain configuration while the condensation products of these latter acids with aromatic aldehydes are lactols. The mesityl derivatives constitute exceptions in both series. These findings necessitate a revision of some of the earlier literature.

The investigation of the condensation products of γ-ketonic esters (I) and aromatic aldehydes showed certain inconsistencies between the para-substituted benzoyl series (X = Cl, Br, OCH_3) and the unsubstituted ketonic ester series (X = H) (2). It was postulated that the condensation products of benzaldehyde and methyl α-phenyl-β-benzoylpropionates gave lactols (II) when chloro-, bromo-, or methoxy-substituents were present in the para-position of the benzoyl group. In the case where X = H, it was concluded that, on the basis of the available experimental evidence,* the condensation product was the isomeric open-chain acid (III). The fact that substituents such



I II III

as methoxy and chloro, which have opposite electrical effects, produce a cyclized compound suggests that the unsubstituted compound should also be cyclic (II, X = H). The problem was therefore reopened with a view to resolving this discrepancy by means of ultraviolet and infrared absorption curves.

As a preliminary step, the ultraviolet and infrared spectra of several α-aryl-β-aroylpropionic acids, which serve as starting materials in the synthesis, were examined. The infrared spectra for these substances (Table I, with the exception of I*m*) all show a typical α,β-unsaturated carbonyl band at about 6.0 μ and an acid band at about 5.9 μ. The ultraviolet absorption spectra show a short-wavelength band in the region 242 mμ for I and I*j*; this is associated with the benzoyl absorption (cf. acetophenone, λ 245, ε = 10,000) (5) and is shifted slightly to longer wavelengths for those substances having an electron-donating

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Contribution from the Kodak Research Laboratories, Rochester 4, New York. Issued as Communication No. 1787.

**In the original work on these lactols and aroylpropionic acids, their behavior, when they were treated quantitatively with an excess of methylmagnesium iodide, was used as a basis for determining structures. Although there were a few discrepancies, in view of the general agreement, it appeared reasonable to draw inferences from the experimental results. It is now obvious that the Grignard reaction is not a reliable tool for distinguishing between possible tautomeric structures.*

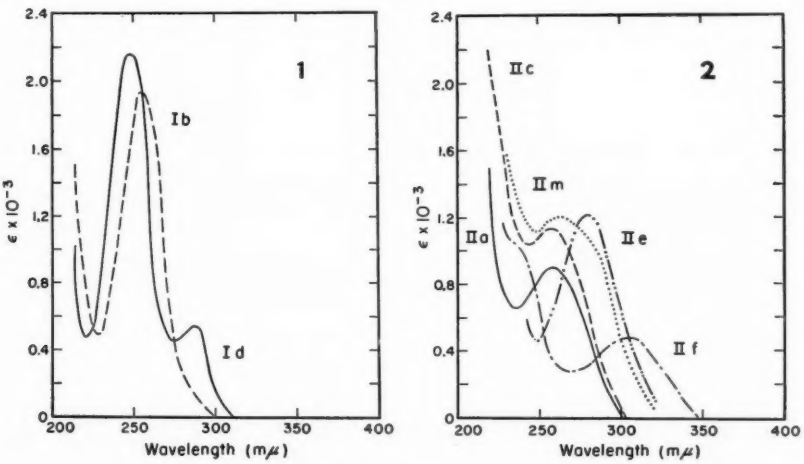
TABLE I

SPECTRAL DATA OF β-AROYLPROPIONIC ACIDS, $R_1CH(COOH)-CH_2COR_2$

	R_1	R_2	m.p.,°C.	Infrared λ_{acid}	Infrared λ_{CO}	Infrared λ_{dimer}	Ultraviolet λ_{max}	Ultraviolet $\epsilon\times10^{-3}$
I*a*	C_6H_5	4-FC_6H_4	161	5.90	5.98	3.8–3.9	255	19.5
I*b*	C_6H_5	4-BrC_6H_4	160	5.87	5.93	3.6–3.9	255	19.5
I	C_6H_5	C_6H_5	150	5.9	5.97	3.7	242	14.6
I*c*	C_6H_5	Mesityl	172	5.87	5.93	3.7		
I*d*	$CH_2O_2C_6H_4$	4-ClC_6H_4	189	5.9	5.97	3.7	248	21.0[a]
							287	5.5
I*e*	H	Mesityl	109	5.86	5.93	3.7		
I*f*	H	4-ClC_6H_4	130	5.9	5.95			
I*g*	H	4-$CH_3C_6H_4$	129	5.9	5.95			
	Methyl esters							
I*h*	$CH_2O_2C_6H_4$	4-ClC_6H_4	109				249	21.6
							288	5.4
I*j*	$CH_2O_2C_6H_4$	C_6H_5	121				242	19.2
							286	5.5
I*k*	C_6H_5	4-$CH_3C_6H_4$	112				252	18.0
I*l*	C_6H_5	C_6H_5	85–86	5.79	5.95			
I*m*	C_6H_5	Mesityl	60–61	5.82			258	0.57
							251	0.90
							263	0.52
I*n*	C_6H_5	4-BrC_6H_4	120					

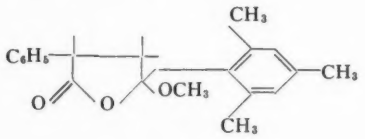
[a] *The spectrum of Id in 0.1 N NaOH has a λ_{max} at 255 mμ ($\epsilon = 35.0\times10^{-3}$) and a shoulder at 290 mμ.*

substituent in the benzoyl residues as in I*b*, I*d*, I*h*, and I*k*. The long-wavelength band in I*d*, I*h*, and I*j* arises from the independently absorbing methylenedioxyphenyl moiety (see Fig. 1). On the basis of the evidence just given, it is



FIGS. 1 AND 2.

clear that these substances exist with the open-chain configuration* in the solid state and in dilute solution. The one exception is methyl β-mesitoyl-α-phenylpropionate (I*m*), the spectrum of which shows clearly that it is the derivative of butyrolactone and has structure (IV).

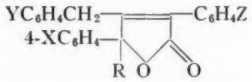


IV

The ultraviolet absorption spectra of lactols of the type II are collected in Table II. The maximum absorption of II*a*–II*n* occurs at about 260 mμ with a molar absorptivity of about 10,000.

TABLE II

SPECTRAL DATA OF SOME LACTOLS AND THEIR DERIVATIVES

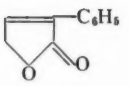


						Infrared		Ultraviolet			
										In alkaline soln.	
II	R	X	Y	Z	m.p.,°C.	CO	OH	λ_{max}	$\epsilon\times10^{-3}$	λ_{max}	$\epsilon\times10^{-3}$
a	OH	H	H	H	147	5.75	2.8	258	10.0	247	14.6
b	OH	Cl	H	H	134	5.75	2.8	260	10.5	257	16.9
c	OH	Br	H	H	157	5.85	3.1	259	11.4		
d	OH	CH_3O	H	H	122	5.85	3.1	267	10.2	280	16.0
e	OH	H	2-CH_3O	4-CH_3O	126	5.75	3.0	281	10.4		
f	OH	Cl	H	CH_2O_2	153	5.80	3.1	305	7.0		
g	OCH_3	H	H	H	119	5.75		260	10.5[a]		
h	OCH_3	Cl	H	H	82	5.75		260	11.1[a]		
j	OCH_3	Br	H	H	78	5.70		260	10.5		
k	AcO	H	H	H	128	5.65		260	10.0		
l	AcO	Cl	H	H	159	5.67		260	10.7[b]		
m	AcO	Cl	CH_2O_2	H	174	5.67		258	12.0		
n	Cl	C_6H_5	H	H	150	5.63		260	22.4		

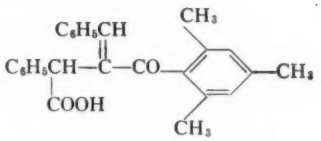
[a]*Same in basic and acetic solutions.*
[b]*Ring opened by alkali.*

The unsaturated lactone (V) has been previously observed to have an absorption maximum at 257 mμ with an extinction coefficient of $\epsilon = 9820$ (4). This similarity in ultraviolet absorption of the lactols and the lactone (V),

**These acids (see Table I) show approximately one active hydrogen and two additions by Grignard analyses; the reagent, in butyl ether, was added to the substance in xylene. These results are at variance with those previously reported (which were done entirely in butyl ether) and with the anticipated results, i.e., one addition and one active hydrogen; the corresponding esters show three additions, as expected. Here again, the mesityl derivative, Ie, shows anomalous results, i.e., 0.0 addition and 3.2 active hydrogen. It must be concluded that the method of Grignard analysis is of little use as a diagnostic tool in this series.*



V

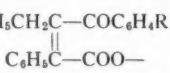


VI

together with the infrared spectra which show a band at $5.75 \pm 0.10\ \mu$, is characteristic of all members of the series and is associated with the carbonyl oxygen of the five-membered ring. Electron-donating substituents in the lactols in positions other than the Z-position (see Table II) do not affect the ultraviolet absorption. In contrast, alkoxy substituents in the Z-position, as in *e* and *f*, produce a bathochromic shift to 281 mμ and 305 mμ, respectively. This suggests that the ultraviolet absorption in this series of lactols is of the styrene type (see Fig. 2). The mesityl derivative (3), on the basis of its ultraviolet (λ_{max} 285 (ϵ = 16,300)) and infrared spectra (5.87 μ and 6.07 μ), is still regarded as the open-chain acid (VI). It shows one active hydrogen (COOH) and one addition (1,4-addition to α,β-unsaturated ketone linkage).

The addition of base to the spectral solution of *a* and *d* produces a small hypochromic shift in *a* and *b*, and a bathochromic shift in the spectrum of *d*; increased absorption was noted in all cases. The maxima for these three substances are presumably due to the benzoyl group functioning freely in the open-chain anionic form since acetophenone and its 4-chloro and 4-methoxy derivatives have maxima in approximately the same position (see Table I for the comparison).

The chalcone absorption which one might expect for this ionic substance (VII) is suppressed by reason of the nonplanarity of the molecule. Steric

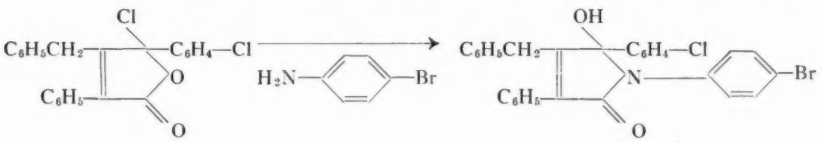


VII

considerations show that the planarity of such a system must be strongly hindered.

The addition of acid or bases to the spectral solutions of the methyl ethers *g* and *h* effected no essential change in either the magnitude or the wavelength of absorption, thus indicating a stable cyclic structure in the case of the methyl ether.

Finally, the structure of the reaction product obtained from the reaction of the cyclic chloride (VIII) with *p*-bromoaniline (1) has been revised to that



VIII IX

of the lactamol (IX). The ultraviolet absorption spectrum has a $\lambda_{max} = 248$ ($\epsilon = 26{,}000$) and the infrared shows a strongly developed OH bond. Both of these properties are in agreement with the structure assigned.

In view of these findings, the structure of the compounds described (1, 2, 3) should be revised accordingly, i.e., all mesityl derivatives and compound IIg and its derivatives, the chloride, acetate, and ester. The latter substances are now assigned a cyclic structure.

ACKNOWLEDGMENT

We are indebted to Professor R. E. Lutz, of the University of Virginia, for lending us a doctorate thesis in advance of its revision for publication.

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REACTIONS OF ARYLSULPHONIC ESTERS

V. AN INTERPRETATION OF ACTIVATION ENERGIES OF SOLVOLYSIS OF METHYL BENZENESULPHONATE IN MIXED HYDROXYLIC SOLVENTS[1]

By J. B. Hyne[2] and R. E. Robertson

ABSTRACT

The rates of solvolysis of methyl benzenesulphonate at 50° and 75° C. in several binary aliphatic alcohol–water mixtures have been determined over the composition ranges. The derived activation energies are compared with those calculated from an extended form of the equation employed in accounting for solvolytic activation energies in pure hydroxylic solvents. The physical significance of the equation is discussed in terms of a spectrum of solvolytic mechanisms covering the range between S_N1 and S_N2 mechanisms. The equation predicts activation energy values well within the experimental uncertainty. Product ratio and activation entropy data are shown to be in keeping with the reaction mechanism proposed.

INTRODUCTION

In the previous paper of this series (8) we established a semiempirical equation relating the activation energies of solvolyses of benzenesulphonic esters in pure hydroxylic solvents. The success of this equation in predicting the activation energies of solvolyses in pure solvents prompted us to attempt to apply a similar treatment to the solvolyses of benzenesulphonic esters in mixed hydroxylic solvents. In this paper we have extended the original equation to enable the mixed solvent work to be treated and show that remarkably good prediction of the behavior of activation energy with solvent composition is possible.

Several other workers (2, 5, 6, 7) have recently made kinetic studies of solvolytic reactions in mixed solvents, notably Tommila and co-workers (16, 17, 18, 19, 20), but in most of these cases only one of the solvent species is solvolytically reactive. In the present work both hydroxylic solvents are reactive and the success of the treatment of activation energies employed is shown to be consistent with the intermediate mechanism (S_N12) postulated in the previous paper (8) for solvolyses in pure solvents.

EXPERIMENTAL

(*a*) *Preparation of Materials*

Methyl benzenesulphonate.—Eastman Kodak White Label further purified by fractional recrystallization from the melt to constant melting point, 4.50° C.

Water.—Distilled water passed through an ion exchange column (13).

Methanol.—Reagent grade material distilled from 50 gm. magnesium per liter at 64.6°–64.7° C. at 760 mm.

Ethanol.—Stock material distilled from 20 gm. of sodium and 30 ml. diethyl phthalate per liter at 78.4°–78.5° C. at 760 mm.

Isopropanol.—Stock material distilled from 50 gm. aluminum per liter under nitrogen flow through a 20 plate Stedman column at 82.2°–82.4° C. at 760 mm.

Tert-butanol.—Stock material purified by fractional recrystallization from the melt to constant m.p. 25.0° C. (three recrystallizations).

[1]*Manuscript received January 23, 1956.*
Contribution from the Division of Pure Chemistry, National Research Council, Ottawa, Canada. Issued as N.R.C. No. 3977. This paper was presented at the 129th Meeting of American Chemical Society, Division of Organic Chemistry, Dallas, Texas, April, 1956.
[2]*National Research Council of Canada Postdoctorate Fellow 1954–56.*

Benzenesulphonic acid.—Eastman Kodak (practical) used without further purification.

(*b*) *Preparation of Solutions*

Stocks of all solvent mixtures were prepared by weight. Approximately 0.1 gm./liter of benzenesulphonic acid was added to the stock solvent mixtures as a backing electrolyte. Working solutions were prepared in 100 ml. lots immediately prior to each run, 0.1 (±0.01) gm./liter of methyl benzenesulphonate being added from a previously calibrated capillary pipette.

(*c*) *Method*

The conductimetric method described by Robertson (13) was used down to 0.5 mole fraction of water. Conductance cells were not degassed in view of the risk of altering the composition of the solvent mixture. No complications arose from air bubbles on the electrodes. Owing to the known variation of degree of dissociation of benzenesulphonic acid with concentration in low dielectric solvent mixtures, several check determinations of rates were made in alcohol–water mixtures near the limit of alcohol concentrations studied. These checks were carried out by a continuous titrimetric method employing a differential colorimeter as end point indicator (14). This method is independent of degree of dissociation of the acid. The checks are shown in Table I. No check was made in methanol as any dependence of degree of dissociation on concentration in methanol–water mixtures would be less than in ethanol–water for which checks were obtained. Rate determinations at 0.738 mole fraction ethanol and 0.496 and 0.750 mole fraction isopropanol were not checked but previous investigations of the effect of dissociation on conductance rate determinations carried out in this laboratory indicate the values obtained are not in error to greater than ±1%.

TABLE I

COMPARISON OF CONDUCTIMETRIC AND TITRIMETRIC RATE DETERMINATIONS

Alcohol	Mole fraction alcohol	Conductimetric $k \times 10^{-4}$ (sec.$^{-1}$)	Titrimetric (14) $k \times 10^{-4}$ (sec.$^{-1}$)
EtOH	0.527	3.47[4] (±0.3%)	3.44[4] (±0.7%)
isoPrOH	0.261	3.98[5] (±0.1%)	3.98[4] (±0.8%)
tert-BuOH	0.182	3.84[5] (±0.3%)	3.85[7] (±0.3%)

All rate determinations in pure alcohols were by the normal titration method described by Robertson (12). Two rate determinations by this titrimetric method in ethanol–water mixtures previously reported by Robertson (12) are also included in Table II, and are in excellent agreement with the curve drawn through points determined conductimetrically.

(*d*) *Temperature Control and Time*

The same thermostatic control and temperature determination apparatus was employed as reported previously by Robertson (13). Temperature was controlled to ±0.003° C. and time measurement was accurate to better than 0.1 sec. per hr.

(e) Precision of Results

The reproducibility of conductimetric rate determinations at both temperatures is recorded in Table II and except in those isopropanol–water mixtures previously mentioned was better than ±0.5%. This precision in k gives a precision of at least ±80 cal./gm-mol. in the activation energy calculated over the 25° C. range. Titrimetric rate determinations were not of the same precision, k's being found to better than ±1% and activation energies to ±150 cal./gm-mol. Although a precision of ±80 cal./gm-mol. is claimed for the activation energy the accuracy is unlikely to be of such a high order in view of the neglect of the ΔC_p of activation. The hydrolysis of methyl benzenesulphonate has a ΔC_p of activation of −31.6 cal./°C. and a somewhat lower value for alcoholysis (unpublished). In the absence of ΔC_p data for all water–alcohol mixtures used, however, a comparison of E_a's as calculated is all that is possible at present. A similar error would be present in all determinations, however, and from a comparative viewpoint the results do not lose significance.

TABLE II

SOLVOLYTIC RATE DATA FOR METHYL BENZENESULPHONATE IN WATER–ALCOHOL MIXTURES AT 50.0 AND 75.0° C.

Alcohol	Reference	Mole fraction alcohol	Vol. fraction alcohol	Dielectric constant of mixture D_{20}	$k\times10^{-5}$ (sec.$^{-1}$)	± % k	t(° C.)	$k\times10^{-4}$ (sec.$^{-1}$)	± % k	t(° C.)	E_a(obs.) (cal./gm-mol.)	E_a(calc.) (cal./gm-mol.)	ΔE_a	log PZ_{50}(obs.)
	(9)	0.000	0.000	80.4	19.66	0.4	50.003	19.34	0.2	74.906	20,520	20,470	+ 50	10.1811
Methanol		0.052	0.109	76.5	17.58	0.1	49.868	17.16	0.3	74.894	20,302	20,490	−188	9.976
		0.147	0.279	69.4	13.61	0.8	49.868	13.24	0.3	74.895	20,271	20,574	−303	9.844
		0.255	0.434	62.4	10.23	0.2	49.985	9.980	0.4	74.893	20,387	20,676	−289	9.798
		0.499	0.689	49.5	5.705	0.1	49.985	5.555	0.2	74.633	20,556	20,911	−355	9.658
	(12)	1.000	1.000	32.4	1.63		50.0	1.09		70.0	20,973	21,264	−291	9.317
Ethanol		0.026			17.66		49.888							
		0.071	0.199	70.8	13.95	0.5	49.910	13.40	0.3	74.901	20,249	20,376	−127	9.840
		0.111	0.288	66.1	10.93	0.1	49.881	10.64	0.3	74.892	20,277	20,354	− 77	9.753
		0.134	0.334	63.6	9.900	0.4	49.888	9.396	0.1	74.892	20,051	20,346	−295	9.557
		0.202						7.152	0.1	74.893				
		0.225	0.485	54.9	6.770	0.5	49.844	6.660	0.5	74.911	20,371	20,346	+ 25	9.608
	(12)	0.236			6.60		50.0							
		0.382			4.670	0.7	49.770							
		0.386	0.671	43.6	4.578	0.2	49.883	4.415	0.1	74.633	20,376	20,372	+ 4	9.442
		0.527	0.783	36.8	3.540	0.5	49.869	3.474	0.3	74.905	20,349	20,388	− 39	9.311
	(12)	0.552			3.34		50.0							
		0.738	0.901	30.1	2.330	0.1	49.887	2.298	0.2	74.887	20,394	20,383	+ 11	9.160
	(9)	1.000	1.000	25.0	rates at 70, 80, and 90° C.						20,400	20,354	+ 46	8.847
Isopropanol		0.025	0.097	74.7	16.81	0.1	49.867	15.81	0.4	74.893	19,970	20,350	−380	9.732
		0.060	0.212	67.7	11.40	0.1	49.886	10.90	0.3	74.900	20,118	20,225	−107	9.663
		0.126	0.379	56.5	6.490	0.2	49.867	6.453	0.3	74.895	20,466	20,089	+377	9.653
		0.264	0.604	40.4	4.141	0.4	49.869	3.985	0.1	74.891	20,175	19,960	+215	9.262
		0.496	0.807	26.0	2.631	0.5	49.886	2.422	0.1	74.900	19,779	19,836	− 57	8.795
		0.750	0.927	20.7	1.740	0.2	49.886	1.540	0.1	74.900	19,429	19,607	−178	8.381
		1.000	1.000	18.6	0.8191	0.1	49.886	0.6985	0.2	74.900	19,150	19,414	−264	7.870
tert-Butanol		0.025	0.117	72.2	14.94	0.2	49.978	14.25	0.2	74.894	20,185	20,250	− 65	9.825
		0.050	0.214	65.0	9.520	0.1	49.978	9.027	0.3	74.894	20,133	20,090	+ 43	9.595
		0.102	0.371	52.7	5.543	0.2	49.978	5.315	0.1	74.893	20,234	19,858	+376	9.429
		0.182	0.538	38.4	4.026	0.1	49.969	3.845	0.3	74.897	20,197	19,674	+523	9.265

RESULTS

In Table II are collected the observed rates and percentage errors at each composition for the two temperatures employed. In all calculations the following values of standard constants were used: $T°$ A. $= 273.16+t°$ C.; $R = 1.987$; $\log_e 10 = 2.3026$. Solvent composition is given as both mole and volume fraction for later convenience as is the dielectric constant of the solvent mixtures (1). The Arrhenius activation energy derived from the observed rates, E_a(obs.), and the corresponding log PZ value at 50° C. are also recorded.

APPLICATION OF EQUATION TO MIXED SOLVOLYSIS OF METHYL BENZENESULPHONATE

The semiempirical equation of the previous paper (8)

$$[1] \qquad E_a = -47.18(D-\alpha+1.43(MV))+25{,}580$$

is not in suitable form to handle mixed solvolysis since the (MV), molecular volume, term is composite in this case. The (MV) term, however, can be expressed as a function of the volume fractions (ν) and molecular volumes (MV) of the two components of the solvent mixture and the extended equation

$$[2] \quad E_a = -47.18(D-\alpha+1.43(\nu_{H_2O}(MV)_{H_2O}+\nu_{alcohol}(MV)_{alcohol}))+25{,}580$$

can be applied in the mixed solvolyses cases. D is the dielectric constant of the solvent mixture at 20° C. and α is a constant characteristic of the ester. The α values for various benzenesulphonic esters were established in the previous paper (8) based on an arbitrary value for methyl benzenesulphonate of $\alpha = 0$. The E_a(calc.) values for the solvent compositions studied were calculated from equation [2] and are compared in Table II with the E_a(obs.) values obtained directly from the observed rates. Fig. 1 compares the observed and calculated values plotted for each solvent mixture across the composition range. The most striking feature of the comparison is the prediction by the extended equation of the reversal of dependence of activation energy on solvent composition on varying the alcohol component through the series methanol, ethanol, isopropanol, *tert*-butanol. In all but a few instances the agreement between E_a(obs.) and E_a(calc.) is good to 300 cal. In Figs. 1(*b*) and 1(*c*), an alternative dotted line is drawn through the experimental points at the aqueous end of the solvent composition range. This arises from doubt as to the accuracy of the determined E_a at approx. 0.13 mole fraction alcohol. The individual rate determinations leading to these values were quite reproducible but the abnormal behavior of the log PZ function in Fig. 4 at these same solvent compositions suggests that they may be in error. This source of doubt, however, does not affect the validity of the general trend observed.

To test the validity of the extended equation in cases where α was not zero, two previous results of Robertson (12) for the activation energy of mixed solvolysis in 50/50 v/v ethanol–water of isopropyl benzenesulphonate ($\alpha = 42$) and isopropyl *p*-methyl benzenesulphonate ($\alpha = 55$) were compared with the calculated values. The comparison is shown in Table III.

The agreement is well within the experimental error of the E_a's showing the validity of equation [2] when α is not zero.

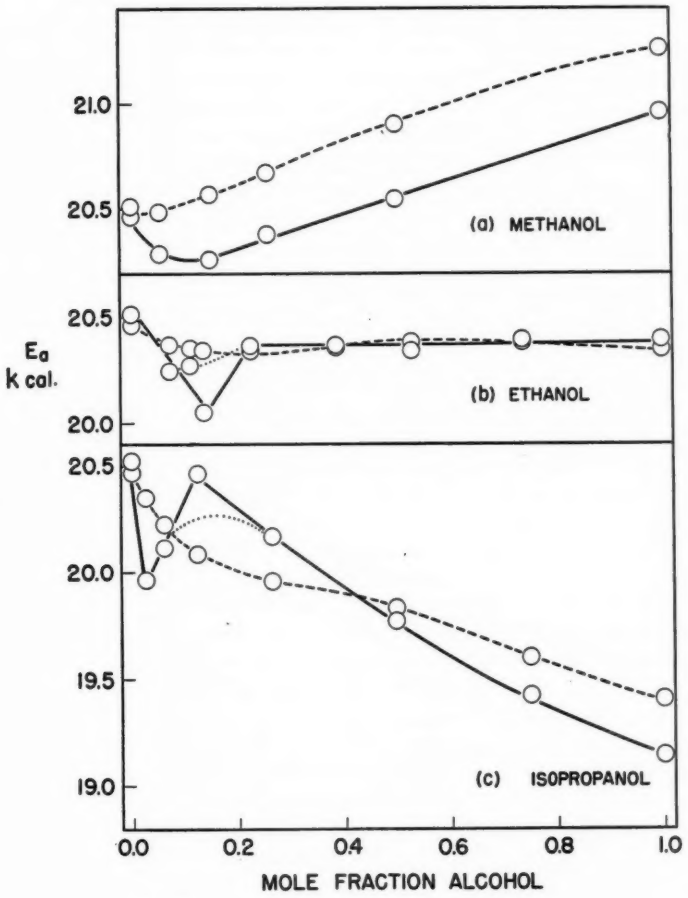


FIG. 1. ——— Observed. - - - - Calculated.

TABLE III

Ester	α^*	Mole fraction ethanol	Vol. fraction ethanol	Dielectric constant mixture D_{20}	E_a(obs.) (cal./gm-mol.)	E_a(calc.) (cal./gm-mol.)	ΔE_a
isoPr-*p*H	42	0.236	0.500	54	22,259	22,370	−111
isoPr-*p*Me	55	0.236	0.500	54	22,843	22,997	−154

α values from previous paper this series (8).

DISCUSSION

(a) *Proposed Mechanism of Mixed Solvolysis*

The S_N12 spectrum of mechanisms proposed in the previous paper (8) and envisaged as operative in all solvolytic reactions intermediate in mechanistic character between the limiting S_N2 and S_N1 types is based upon the principle

that charge separation in the breaking bond of the ester precedes the onset of covalent interaction between the ester molecule and the solvent species. When covalent interaction and charge separation take place at the same point on the reaction parameter the mechanism is of the accepted S_N2 type (the one-stage process); as covalent interaction enters progressively later in the reaction relative to the charge separation, there is a tendency to formation of solvation stabilized intermediate ester species. These intermediates are characterized by a specific degree of charge separation in the breaking bond and the stability of the intermediate arising from solvation will be greater for greater charge separation. In the limit, as covalent interaction enters very late in the reaction process, charge separation proceeds to completion and a solvation stabilized ionic intermediate is formed characteristic of the pure S_N1 mechanistic type. It is, therefore, proposed that there is a *gradual* transition in mechanistic type from S_N2 to S_N1 so that each solvolytic reaction having intermediate character can be placed in its relative position on the mechanistic spectrum. It is impossible on the evidence presently available to do more than guess at what point in the spectrum an actual intermediate appears. Doering and Zeiss (4) appear to favor the idea that an intermediate of very low stability is formed immediately the reaction characteristics depart from pure S_N2 behavior. This may be the case but the possibility remains that some intermediate S_N12 mechanisms having marked S_N2 character may be operative in which no true stabilized intermediate exists. The location of the range occupied by the solvolytic mechanisms of the benzenesulphonic esters on the S_N12 mechanistic spectrum cannot, therefore, be established conclusively. For simplicity of presentation, however, we have assumed that the most "S_N2-like" of these solvolytic mechanisms, viz. that of solvolysis of methyl benzenesulphonate, is characterized by the formation of a solvation stabilized intermediate. In Fig. 2 are shown the proposed stages in the mechanism of mixed solvolysis of methyl benzenesulphonate. The solvent stabilized intermediate ester species, involving

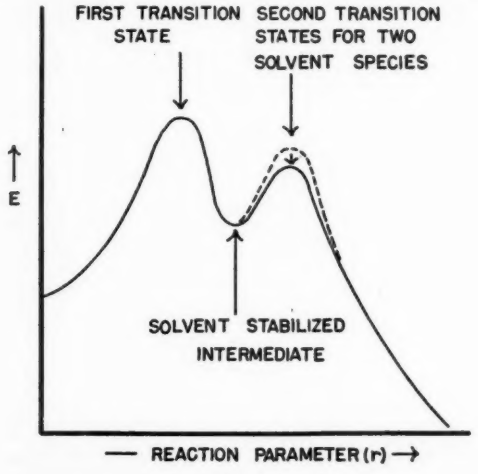
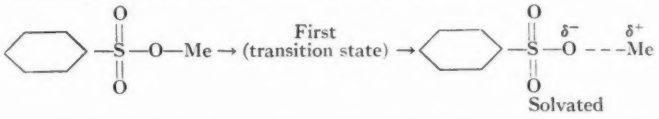


FIG. 2.

charge separation in the ester bond eventually to be broken, is reached through a rate-determining transition state with very little if any covalent interaction between ester and solvent molecules. This transition state, and subsequent intermediate, are then common to both the hydrolysis and alcoholysis in the case of mixed solvolysis and this being the rate-determining stage the observed activation energy is associated with this single process.



In the case of solvolysis in pure solvents the detailed nature of solvation of the intermediate was not defined (8) since all solvating species were identical. In mixed solvolysis, however, we have two hydroxylic solvent species participating in the solvation of the intermediate. There will be competitive solvation by both components of the solvent mixture, the extent to which each species will be involved in the primary solvation shell depending upon the relative activity of the two species in the solvent mixture. The positions of the species in the solvation shell must be energetically equivalent. This is a necessary condition for a common solvent stabilized intermediate for both subsequent reactions. On passing to the second transition state one of the solvating species must attain a preferred covalent reaction position relative to the charge separated ester bond. The species adopting this position, either water or alcohol, will be determined by the relative abundance of the two species in the solvation shell which in turn is dependent upon the relative activities of the two species in the solvent mixture. The ratio of the products of the hydrolysis and alcoholysis should then be dependent upon the activity of the respective solvents

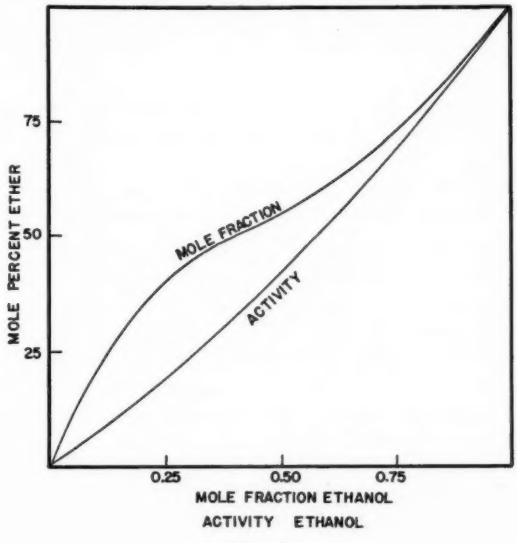
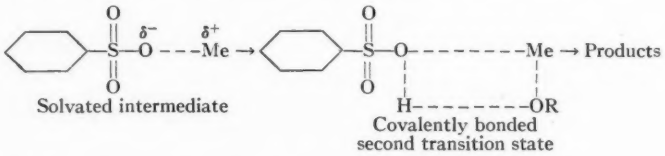


FIG. 3.

in the mixture. In Fig. 3 the mole per cent of ether (product of alcoholysis) is plotted against both mole fraction and activity of ethanol in the solvent mixture. The dependence of the ether product percentage on activity of the alcohol shows only slight negative deviation from linearity. The details of this product ratio work will be published shortly (10). Covalent interaction between one of the solvation shell molecules and the ester in the second transition state will be characterized by a specific activation energy for each reacting solvent species. Two possible transition states therefore exist in the second stage but of lower energy than the first common transition state so that they are not involved in the rate-determining process as shown in Fig. 2.



(*b*) *Failure of Equation in Highly Aqueous Solvent Mixtures*

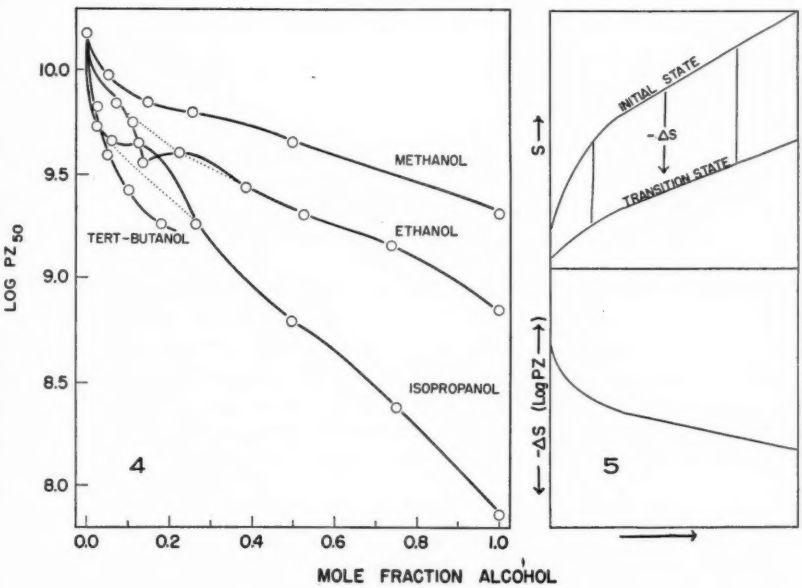
Inspection of Fig. 1 shows that equation [2] fails to predict the marked minimum in E_a(obs.) noted in highly aqueous compositions. Similar behavior was noted by Tommila (16) in recent work on the solvolysis of benzenesulphonic esters in acetone–water and dioxane–water mixtures. Tommila offers a preferential solvation explanation for this behavior stating that the minimum indicates high solvation and high polarity of the initial state. We would suggest that the minimum observed in the work presented here is indicative of preferential solvation by the alcohol component. In such circumstances the microdielectric about the ester molecule would be markedly reduced below that expressed by the bulk dielectric (D_{20}) for the mixture and charge separation would consequently be less, favoring a more "S_N2-like" mechanism with a lower over-all activation energy. Furthermore it is seen from Fig. 3 that the plot of product ratio against mole fraction of alcohol shows an excess of the alcoholysis product (ether) at high water compositions in keeping with the suggestion that there is preferential alcoholic solvation. Attention is also drawn to the work of Martin and Brown (11) and others (3, 15) who have shown by various studies that at high aqueous concentrations in alcohol–water mixtures the water molecules tend to form water–water bonds preferentially within the solvent lattice. Greater energy would then be required to remove water molecules from the lattice for a solvation role than to remove alcohol molecules. Once a sufficiently high alcohol concentration has been reached to break up the quasi-crystalline water lattice the water will be more readily available for solvation. It is, therefore, not surprising that the simple relationship used to describe the solvent participation, viz. the molecular volume expression, does not reflect this special property of the system.

An attempt has been made to apply equation [2] to solvolysis in water–acetone and water–dioxane mixtures. The equation fails to predict the behavior of the activation energy over the composition range. This could be the result

of simplifying assumptions made in establishing the original equation in the previous paper of this series (8). Here it was assumed that all solvent–solvent hydrogen bonds were of the same O–H - - - - O energetic type. This may be an acceptable approximation in mixtures of hydroxylic solvents but with the carbonyl and ether oxygen groups of acetone and dioxane the validity is questionable.

(c) Discussion of Mixed Solvolytic Activation Entropies

In discussing the variation of entropy of activation (ΔS) in terms of the log PZ function for the solvolysis of a given ester in a series of pure solvents (see Part IV this series (8)) we suggested that the increase in the negative ΔS value was due to a more rapid increase in the entropy of the initial state compared with the increase in entropy of the transition state as we proceeded along the solvent series. As expected the negative ΔS value also increases in passing through the composition range of mixtures of two solvents in the series. Generally speaking the increase in $-\Delta S$ (decrease in log PZ) bears a roughly linear relationship to the mole fraction of the alcohol (Fig. 4). There are some interesting deviations, however, which can be explained on the basis of the principles employed in discussing the behavior of the activation energies.



FIGS. 4 AND 5.

In all four mixed solvent cases studied here there is an initial drop in log PZ (increase in $-\Delta S$) tending to level off as the mole fraction of alcohol increases and then proceeding more or less linearly to the pure alcohol. Let us consider

only the case of the methanol–water mixtures since the other cases behave similarly. We have, from previously discussed evidence, suggested that there is preferential solvation by the alcohol component in highly aqueous mixtures. How will such preferential solvation affect the activation entropy? In both the initial and transition states preferential solvation by alcohol over water would result in higher entropy because of the reduction in degree of ordering possible about the ester molecule in the case of the bulkier alcohol molecule. In the initial state this increase will be more marked than in the transition state owing to the weaker orientation forces of the dipolar ester molecule. Although the same steric argument applies in orientation about the transition state the stronger orientating forces arising from the partial charges will reduce the effect and the entropy will increase more slowly as a function of composition. In Fig. 5 the suggested behavior of the entropies of the initial and transition states is shown and the consequent behavior of the difference in entropy ($-\Delta S$) plotted. As is seen an initial increase in $-\Delta S$ (decrease in log PZ) is predicted followed by a linear trend to pure alcohol in a manner similar to the observed data plotted in Fig. 4.

Without introducing any further modifications of the model upon which the activation energy behavior was explained we can interpret the general behavior of the activation entropies and by refining the picture of solvent–solvent interaction in mixed solvents we can qualitatively account for minor deviations from this general behavior.

CONCLUSIONS

By extension of the semiempirical equation used in the previous paper of this series to correlate the activation energies of solvolyses of benzenesulphonic esters in pure solvents we have shown that solvolytic activation energies in mixed hydroxylic solvents may be treated in a similar manner. While the extended equation accounts for the gross behavior of the activation energies as a function of solvent composition further refinements are required in the molecular model used to account for minor deviations not predicted by the equation. These modifications are shown to be in keeping with the conclusions of other workers and are satisfactorily applied in a suggested treatment of the activation entropies. The work presented in this paper serves as a further test of the validity of the basic assumptions made in the previous paper in establishing the form of the semiempirical equation for solvolytic activation energies.

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A METHOD OF RECORDING a-c. POLAROGRAMS ON A CONVENTIONAL d-c. POLAROGRAPH[1]

By D. M. Miller[2]

ABSTRACT

An increase in the usefulness of the recording polarograph is obtained by a modification which allows either a-c. or d-c. polarograms to be obtained from it. A description of such a modification performed on the Sargent Model XXI is given in detail. A comparison of a-c. and d-c. polarography is made and illustrated by polarograms obtained from this instrument.

INTRODUCTION

Polarography with alternating currents has been investigated by a number of authors but the most extensive work is that of Breyer *et al.* (*vide infra*). Basically the method consists of impressing a small sinusoidal alternating voltage of low frequency on the direct potential applied to a dropping mercury electrode. This results in an applied e.m.f. which varies between limits determined by the amplitude of the a-c. voltage (ΔE, Fig. 1). Should the current

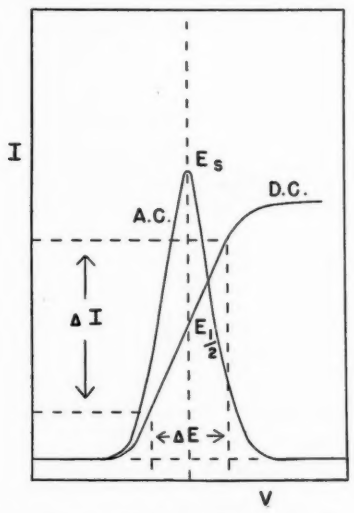

FIG. 1. Comparison of a-c. and d-c. polarograms.

be higher at the upper limit than at the lower limit of this voltage variation (as on the rising portion of the d-c. polarogram) an alternating current ΔI would be produced. This alternating current is measured as a function of the impressed direct voltage resulting in a plot which is essentially the derivative

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of the normal d-c. polarogram. Thus the waves produced in conventional polarography are replaced by a series of peaks, the summit potential (E_s) of which corresponds to the half wave potential ($E_{\frac{1}{2}}$) of the depolarizer (4).

A characteristic of this method is that only reversible electrode reactions give an a-c. peak. Breyer, Bauer, and Hacobian (3) have discussed the conditions which lead to reversible and irreversible electrode processes. They point out that reversible electrode reactions may be either polarographically reversible or irreversible depending on relative rates of the diffusive and electrochemical processes, and whether or not secondary reactions occur. Irreversible electrode reactions do not give a-c. polarograms. The reduction of oxygen therefore does not interfere directly in a-c. polarography and in general need not be removed.

Under the proper conditions the height of the a-c. wave produced by inorganic ions is directly proportional to the concentration of the ion (5). Best results are obtained in the range 10^{-4} M to 10^{-3} M with a limit of sensitivity of 10^{-5} M.

Since at the completion of the a-c. wave the current has returned to that of the ground solution, waves at more negative potentials are not affected by those of nobler ions. This means that small amounts of one ion may be determined in the presence of large amounts of ions reduced at more positive potentials, a difficult or impossible procedure with d-c. polarography.

Owing to the higher current obtained with the a-c. polarograph the effect of circuit resistance is much more pronounced. Breyer, Gutman, and Hacobian (6) have used mercury pool electrodes to reduce cell resistance but the author has found the usual H-cell to have an equally low resistance plus the advantage of a reference electrode.

The a-c. polarography of a number of ions has been studied by Breyer, Gutman, and Hacobian (5, 6, 8, 9). Cations were found to produce normal waves while the anions studied (9) produced very sharp anodic waves whose summit potentials did not correspond to their $E_{\frac{1}{2}}$ values but instead appeared at potentials at which discharge began. Further, in contrast to cathodic waves, the anodic processes interfered with each other, the wave heights being reduced by the discharge of compounds at more negative potentials.

Organic compounds were also studied by Breyer and co-workers (1, 2). Most organic compounds are polarographically irreversible as judged by the slope of the $\log(i_d-i)/i$ plots, yet give very good a-c. waves. This is probably due to reversible steps in an over-all irreversible process. Organic compounds are detectable at lower concentrations than are inorganic by the a-c. polarographic method. For example chloranilic acid may be detected as low as 10^{-7} M and methylene blue down to 10^{-6} M. The peaks are usually within ± 50 mv. of the $E_{\frac{1}{2}}$ values. The peak heights plotted against concentration are not straight lines as with inorganic compounds but rise sharply at low concentrations and less sharply as the concentration increases finally approaching a limiting value which is apparently determined by the available electrode surface. These facts indicate that the mechanism of the a-c. polarographic oxidation and reduction of organic compounds is different from that of inorganic.

The advantages of a-c. over d-c. polarography are as follows:

(1) There is no direct interference from dissolved oxygen.

(2) Small amounts of some compounds may be determined in the presence of large amounts of more easily reduced materials.

(3) There is a generally increased sensitivity.

(4) Polarographic waves only 40 mv. apart are clearly separable.

(5) A single measurement at the summit potential can give both $E_{\frac{1}{2}}$ and concentration of the depolarizer.

The greatest advantage of this method would be realized by its use in conjunction with d-c. polarography and it is therefore the purpose of this paper to describe a method of converting a conventional d-c. recording polarograph to one which will produce both a-c. and d-c. polarograms.

APPARATUS

The apparatus as described by Breyer, Gutman, and Hacobian (5, 7) consists of the usual polarographic circuit with the alternating voltage introduced across resistance R_2 (Fig. 2(*a*)). The galvanometer which is connected across

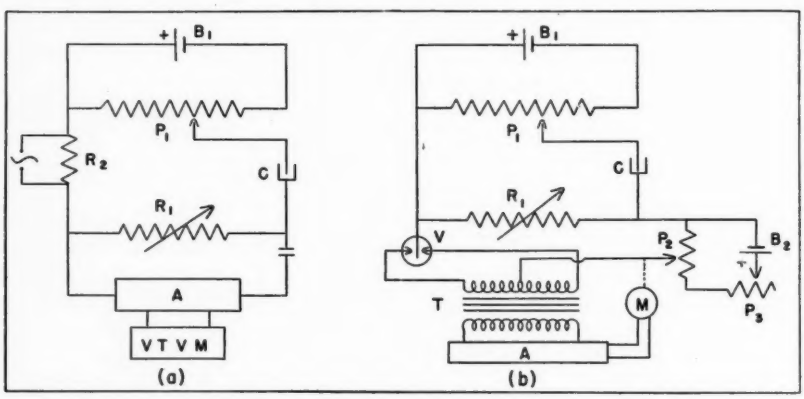

FIG. 2. (*a*) Circuit of a-c. polarograph. (*b*) Circuit of d-c. recording polarograph.

P_1, P_2, P_3—Potentiometers
C —Polarograph cell
A —A-c. amplifier
R_1—Sensitivity selector
V—Vibrator-converter
M—Balancing motor
$VTVM$—Vacuum tube voltmeter

R_1 in d-c. polarography is replaced by a condenser coupled a-c. amplifier and vacuum tube voltmeter which measures only the a-c. current passing through the circuit.

In the present report reference will be made to the Sargent Model XXI Visual Recording Polarograph, but the general methods of modifying this machine should be adaptable to all those which employ a self-balancing potentiometer type recorder utilizing a 60 cycle vibrator-converter and a-c. amplifier.

Fig. 2(*b*) is a schematic circuit diagram of this polarograph as employed in d-c. work. It is similar to that of a manual polarograph, with the exception that the galvanometer has been replaced by a resistor R_1 and recording poten-

tiometer in parallel. The current flowing through the circuit develops a potential across R_1 which is measured by the recorder.

The recorder opposes the unknown e.m.f. across R_1 with a known e.m.f. determined by the position of the sliding contact on calibrated slide-wire P_2. Any difference in e.m.f. between R_1 and P_2 (error signal) is converted to a 60 cycle a-c. voltage by the vibrator V, amplified, and fed into the motor M which then operates the slide-wire in such a direction as to eliminate the difference. The slide-wire is calibrated periodically by reference to a standard cell, to correct for voltage changes in B_2, and any adjustments required made by means of auxiliary potentiometer P_3.

To measure the alternating voltage developed across R_1 when a-c. polarography is employed, B_2 must be replaced by an a-c. source 180° out of phase with the voltage across R_1. Since the error signal is already a-c., the vibrator is no longer necessary and is shorted out. This is the basis of the conversion, and with reference to Fig. 3 the actual details follow.

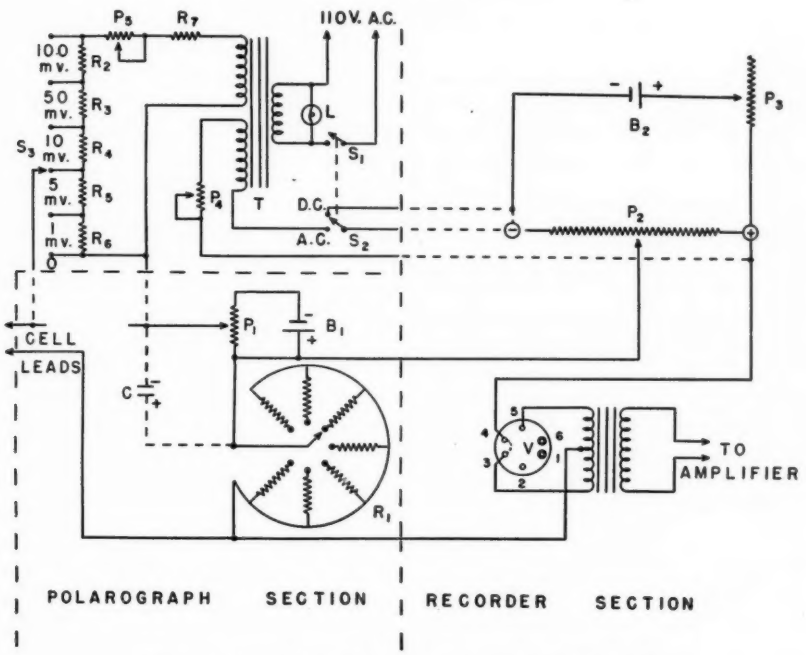

FIG. 3. Wiring diagram for a-c.-d-c. recording polarograph.

C —300–500 μf., 25 W.V.
R_1—Sensitivity selector
R_2—5.0 ohm precision
R_3—4.0 ohm precision
R_4—0.5 ohm precision
R_5—0.4 ohm precision
R_6—0.1 ohm precision
R_7—200 ohm
P_1—Polarograph slide-wire
P_2—Recorder slide-wire
P_3—Recorder balancing resistor
P_4—5000 ohm
P_5—100 ohm
S_1–S_2—DPST switch
S_3—mv. selector switch
V —Vibrator shorting plug
L —110 v. pilot light
T —Hammond 165 X 115 v. primary, 2.5–2.5 v. secondary

The polarograph is housed in a case consisting of two parts, the upper part containing the recorder section, and the lower part the batteries and polarograph section. The a-c. components are located in the lower part outside the polarograph section with controls S_1, S_2, S_3, P_4, and pilot light L mounted on the front of the polarograph below the control panel. P_5 and R_7 are mounted behind these and the transformer is mounted behind the polarograph section near the main power inlet. The a-c. switch S_1 must be on the ungrounded side of the line to ensure that the primary of the transformer is at ground potential when operating on d-c.

The two leads entering the polarograph section do so through a terminal strip. These leads, and all leads added to the polarograph and recorder section, are shown as dotted lines in Fig. 3. A 300 μf. condenser shunts the a-c. signal around P_1 to prevent increasing the resistance to the a-c. as the resistance of P_1 is increased.

Shielding the three leads from the controls to the recorder section does not appear to be essential but is advisable. A six-prong male plug with a shorting wire between terminals 3 and 4 is used to replace the vibrator when operating the polarograph on a-c.

In wiring the transformer the recorder supply is connected first, connections being reversed if the recorder will not read zero with an open cell circuit. The other secondary is connected up in such a way that the recorder needle moves up the scale when the cell leads are momentarily shorted.

Calibration

Since the usual convention is to express a-c. voltage and current in r.m.s. terms switch S_3 reads in mv. r.m.s. The most convenient method of calibration is by means of a calibrated oscilloscope. S_3 is set at "10 mv." (the most commonly used range) and with S_1–S_2 at "a-c.", damping switch "off", and "D.M.E." switch "negative", P_5 is adjusted until a peak to peak voltage of 28.2 mv. is observed on the oscilloscope attached to the cell leads. (If P_5 is mounted behind the panel, the polarograph section must be lifted out for this operation. It may be mounted, however, on the panel as a screw adjustment.) Once adjusted P_5 should require no further attention.

Calibration of the recorder to read in μa. r.m.s. must be made after each use on d-c. This is due to the fact that P_3 is changed by the recorder as the e.m.f. of B_2 alters because of age or replacement. This is easily accomplished by plugging a 1000 ohm precision resistor into the cell lead jack, setting S_3 at "10 mv.", sensitivity at "0.100 μa./mm.", damping switch "off", operation switch at "e.m.f. constant", and adjusting P_4 to give a difference of 100 mm. between "D.M.E." switch "off" and "negative".

Operation

The change from a-c. to d-c. operation is made by putting switch S_1–S_2 at "a-c." and replacing the vibrator in the amplifier by the shorting plug. The normal d-c. polarographic controls apply to a-c. operation as well except for the damping switch which must be "off" during a-c. polarography.

A comparison of a-c. and d-c. polarograms was made using a mixture of six ions in 0.5 M HCl. Fig. 4 shows the actual polarograms obtained and demon-

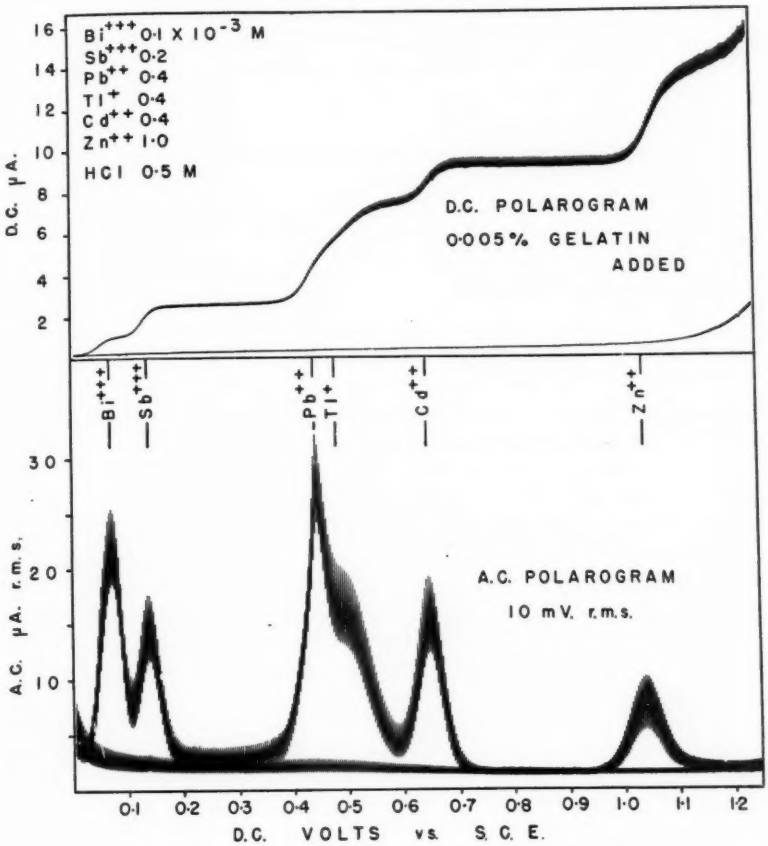

FIG. 4. A-c. and d-c. polarograms of a mixture of ions.

strates the essential advantages of a-c. over d-c. polarography, i.e. increased sensitivity, less interference between waves (Tl^+ much more obvious), E_s more readily measured than $E_{\frac{1}{2}}$, no interference from oxygen (present in the a-c. polarogram).

In general it is felt that the small amount of effort needed to modify the polarograph is more than repaid in increased versatility.

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GRAFT COPOLYMERS OF STYRENE AND METHYL METHACRYLATE

PART I: SYNTHESIS[1,2]

By M. H. Jones

ABSTRACT

A series of graft copolymers of styrene and methyl methacrylate have been prepared by using samples of brominated polystyrene as photochemical initiators for the polymerization of methyl methacrylate. Estimates of the branch chain lengths have been obtained from kinetic and viscosity measurements. In conjunction with the infrared analyses of the total weights of the branches, these have permitted a determination of the frequencies of branching.

INTRODUCTION

There has been considerable interest of late in the preparation of copolymers in which the respective monomer units are arranged in discrete blocks within the polymer molecule rather than distributed randomly. In general, two types of 'block' copolymers can be prepared; that in which two or more groups of repeating monomer units are arranged within a linear molecule and, the second, in which branches of a different monomer are grafted onto the backbone of a homogeneous polymer chain. Obviously there are variants in which the two types of structure can be combined. This paper is concerned with the synthesis of the second kind, namely graft copolymers of styrene and methyl methacrylate of which styrene units comprise the backbone of the molecule and the branches are composed of methyl methacrylate units.

It is probable that branching occurs in a normal radical polymerization through the abstraction of a hydrogen atom from a dead polymer molecule or a growing polymer chain, the resultant radical acting as an initiator for polymerization in the monomer with the growth of a branch. As the activation energy of such a transfer step is generally considerably greater than that of propagation, branching will only become significant at high temperatures or at high conversions when the concentration of polymer is appreciable. Evidence of grafting by transfer in certain systems has been obtained by polymerizing monomers in the presence of large concentrations of a foreign polymer (3, 7, 11, 15). The method has certain disadvantages in that large amounts of homopolymer are formed and, when grafting is small, the product may contain three constituents, an unbranched residue of the initial polymer, the graft material, and the homopolymer produced during polymerization.

An alternative means of grafting involves the use of a polymer containing active groups or atoms distributed along its chain as an initiator for polymerization. Elimination of these groups in the presence of a monomer, either thermally or photochemically, will provide radical centers in the polymer chain at

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which polymerization can start with the growth of branches. It must be supposed that the atoms or radicals produced simultaneously will also initiate polymerization in the monomer and the product will consist of a mixture of graft copolymer and linear homopolymer. As the frequency of branching can be controlled more easily by this method, conditions can be chosen such that all the initiating polymer molecules are branched. In the present work, samples of brominated polystyrene have been used for photochemical initiation (9, 10). Recently, polymethyl vinyl ketone (5, 6), polymethyl acrylates containing per-ester groups (13), and alkylated polystyrene hydroperoxides (12) have all been used as polyradical sources for the synthesis of graft copolymers.

EXPERIMENTAL

Materials

Methyl methacrylate (Matheson, Coleman, and Bell Practical Grade) was shaken three times with 5% solutions of sodium hydroxide to remove the inhibitor, washed with distilled water, and dried over anhydrous sodium sulphate. The product was distilled in an atmosphere of nitrogen at 110 mm. pressure. The second fraction, b.p. 47.0–47.2°C. was retained for the polymerization experiments and given a bulb-to-bulb distillation in vacuum prior to use. The benzene and carbon tetrachloride used as solvents were of reagent grade quality and were dried and distilled before use. For the fractionation experiments, reagent grade methanol was used without further purification.

Procedures

Polymerizations were carried out in calibrated pyrex dilatometers having bulb diameters of 15 mm. and capacities of approximately 12 cc. The dilatometers were sealed to suitable bulbs into which was weighed the brominated polystyrene. The system was evacuated on a high vacuum line and known volumes of the monomer and solvent distilled in from calibrated burette stems. After the mixture had been thoroughly degassed, the system was sealed under vacuum. When the polymer had dissolved, the dilatometer was filled by tipping and sealed off at the end of the capillary.

The photochemical polymerizations were conducted in a thermostat bath at 25.0°C±0.005°C. The windows of the bath were also of pyrex. A General Electric mercury lamp (Type H100-A4) with the envelope removed was used as the light source and the beam was roughly collimated by a quartz lens. The reactions were followed by observing the fall in level of the meniscus in the capillary by a cathetometer. Rates were calculated on the assumption that a contraction in volume of 23.1% corresponds to 100% polymerization (14). At the end of a reaction, the mixture was diluted with benzene to give a 1% polymer solution and the polymer precipitated by dropwise addition to a 30-fold excess of methanol. Polymers were dried to constant weight on a high vacuum line at room temperature and the recoveries obtained were 92–95% of the theoretical.

The reaction products, which consisted of graft copolymer and polymethyl methacrylate, were separated by fractional precipitation using the solvent–

precipitant system benzene–methanol. The precipitant was added slowly to a solution of the polymer mixture (approximately 0.8 gm./100 cc.) at 25°C. until the first sign of gel formation was observed. A known volume of methanol was added in excess, the solution was warmed 10°C. to redissolve the gel and allowed to cool slowly to thermostat temperature. After a period of 18 hr. to allow the gel to settle, the supernatant solution was carefully decanted, the gel dissolved in benzene and reprecipitated. Successive fractions were obtained in a similar manner. The fractions collected before the inflection point of the fractionation curve were assumed to consist of the graft copolymer. To remove small amounts of polymethyl methacrylate which remained as the result of 'tailing', these fractions were combined and reprecipitated as a single fraction at the benzene–methanol composition corresponding to the inflection point of the curve.

The compositions of the individual polymer fractions were determined by infrared analysis using the strong carbonyl absorption band of the polymethyl methacrylate at 1733 cm.$^{-1}$. Trichloroethylene was used as the solvent for these measurements and the compositions were obtained from the optical densities by comparison with a calibration curve prepared from synthetic mixtures of polystyrene and polymethyl methacrylate. Duplicate analyses agreed within 2%. As a check on the analytical values, measurements were also made on the phenyl absorption band of the polystyrene residue at 699 cm.$^{-1}$ where polymethyl methacrylate is transparent.

Viscosity measurements were made in benzene solution at 25°C. with a Ubbelohde type viscometer incorporating a large bulb to permit dilution of the solution *in situ*.

Bromination of Polystyrene

Samples of brominated polystyrene for use as polyradical sources were prepared by the photobromination of a high molecular weight polystyrene. This method was chosen to ensure that substitution occurred preferentially in the carbon chain of the molecule. The starting material, which was believed to have little or no branching, was prepared by thermally polymerizing styrene at 70°C. to a conversion of 10%. Solutions of this polymer (1–2%) in carbon tetrachloride containing various amounts of bromine were degassed, sealed under vacuum, and irradiated with ultraviolet light at 25°C. until the intensity of the bromine color decreased by approximately 50%. Irradiation times were usually 15–20 min. The incident radiation was limited to the wave length region 3500–4800 Å by a Corning Glass filter No. 5113 to reduce any simultaneous photolytic decomposition of the product. At the end of a reaction, the volatile components were removed by vacuum distillation at room temperature and the brominated polystyrene recovered by dissolving in benzene and reprecipitating from methanol. These polymers show a marked increase in absorption over polystyrene in the region 2800–3500 Å. The bromine contents and intrinsic viscosities of various samples are recorded in Table I. The molecular weights given in the last column of this table were derived from the intrinsic viscosity – molecular weight relationship of Ewart and Tingey (4) for unfractionated polystyrenes, i.e. $[\eta] = 0.75.10^{-4}\ M_n^{0.783}$. It is apparent that the bromination

TABLE I

PHOTOBROMINATION OF POLYSTYRENE

Sample No.	% Br	$[\eta]_{25°C.}$	$M_n \cdot 10^{-3}$
Original polystyrene	—	3.16	810
A	2.15	1.30	260
B*	3.18	0.84	150
C	3.85	1.60	340
D	2.60	1.55	325
E	3.16	1.84	400

**Prepared by thermal bromination at 60°C.*

reaction is accompanied by some degradation of the polymer. Attempts to prepare polystyrenes containing aliphatic bromine atoms by copolymerization of styrene with α or β bromostyrene proved unsuccessful (8).

Grafting Reactions

For the grafting reactions, benzene was added as a diluent to reduce the rate and chain length of the branches. All the graft copolymers were soluble in

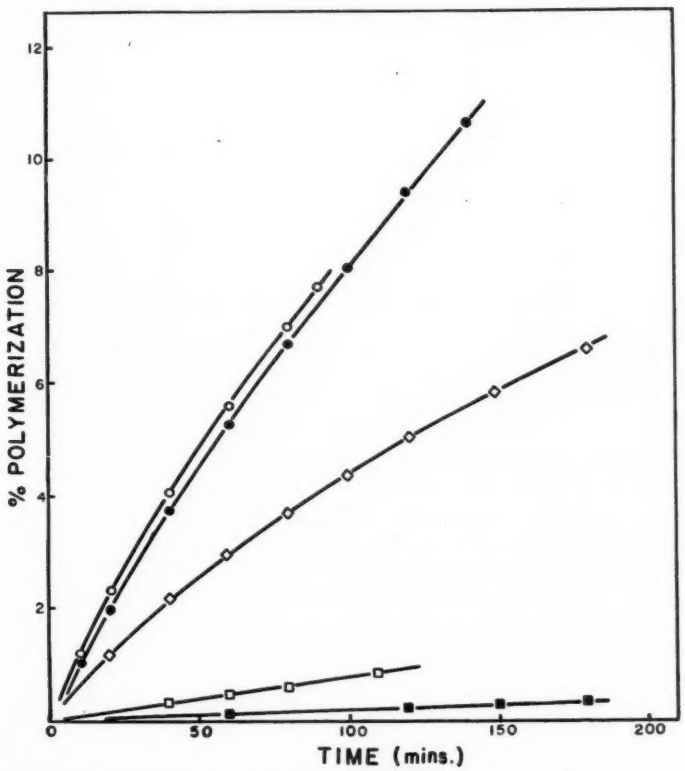

FIG. 1. Reaction–time curves for grafting experiments.
Expt. No. D2, –○–; Expt. No. E3, –●–; Expt. No. A1, –◇–; Pure monomer, no filter, –□–; Pure monomer, filter 584, –■–.

benzene although those with higher degrees of branching dissolved with some difficulty. During polymerization, the radical termination process must, therefore, be mainly disproportionation since termination of growing chains by a combination mechanism would result in cross-linking with the formation of an insoluble network. This condition was observed in branching reactions with styrene (9, 10). Using radioactive initiators, Bevington, Melville, and Taylor (2) have demonstrated that disproportionation occurs twice as frequently as combination in methyl methacrylate polymerization at 25°C.

Typical reaction–time curves for the grafting experiments are shown in Fig. 1 and it is apparent that the rate decreases with extent of polymerization. The rates recorded in Table II are the mean values determined from the total dilatometric contractions. For the series of experiments E1–E4, where poly-

TABLE II

PHOTOCHEMICAL POLYMERIZATION OF METHYL METHACRYLATE AT 25°C. INITIATED BY BROMINATED POLYSTYRENE

Expt. No.	[Polymer], gm. dl.$^{-1}$	[Monomer], moles l.$^{-1}$	Rate. 10^6, moles l.$^{-1}$ sec.$^{-1}$	% Conversion	$\bar{P}_n$ (kinetic)	$[\eta]_{25°C.}$, dl. gm.$^{-1}$	$\bar{P}_n$ (viscosity)
Pure monomer*	—	9.32	2.85				
Pure monomer	—	9.32	11.6				
A1*	1.42	9.19	57	7.11	4900	1.60	4500
A2*	1.40	2.91	9.4	17.8	3100	0.590	1450
D1	1.52	9.18	150	5.75	2050	0.890	2300
D2	1.55	7.14	104	7.87	1800	0.695	1750
D3	1.62	5.11	59	11.2	1650	0.640	1600
D4	1.50	3.00	27	17.5	1250	0.530	1300
E1	1.46	6.68	115	3.72	1450	0.615	1550
E2	1.46	6.68	95	7.43	1700	0.610	1550
E3	1.46	6.68	85	11.2	1900	0.710	1800
E4	1.46	6.68	80	16.4	2050	0.750	1900

**Corning filter No. 5840 used. Incident radiation limited to wave length region 3100–4000 Å.*

merization conditions were identical except that successive reactions were allowed to go to higher conversions, a decrease in the average rate of 35% was observed. The cause of this is not known. It cannot be attributed to impurities in the monomer as the contraction–time curves when α,α'-azo-bis-isobutyronitrile was used as initiator showed no deviations from linearity up to conversions of 10%. In addition, in similar branching experiments with styrene (10), the rate was also independent of the extent of reaction.

If it is assumed that the brominated polystyrene functions solely as an initiator, the mean degree of polymerization, which is also the chain length of the branches, can be calculated from the measured rate of reaction and the kinetic constants available in the literature. From the usual kinetic scheme for vinyl polymerization, it can be shown that the degree of polymerization can be related to the rate of reaction by the expression

$$1/\bar{P} = k_t/k_p + k_t R/k_p^2[M]^2$$

where k_p, k_t, and k_f are the rate coefficients of propagation, termination, and transfer. The chain lengths recorded in Table II were calculated from the above

expression using values of 3.10^{-5} and 260 for k_t/k_p and k_t/k_p^2 respectively (2).

As mentioned previously, the bromine atoms formed in the photochemical step also initiate polymerization in the monomer with the formation of polymethyl methacrylate whose average length should be identical with that of the branches grafted onto the polystyrene chain. Consequently a second method of determining branch length is available. The intrinsic viscosities of the total polymethyl methacrylates recovered from each reaction mixture by fractionation are also given in Table II together with the number average chain lengths derived from the viscosity – molecular weight relationship of Baysal and Tobolsky (1), i.e. $[\eta] = 9.4.10^{-4}\,\bar{P}_n^{0.885}$. The agreement between the values obtained by the two independent methods is surprisingly good.

Isolation and Analysis of the Graft Copolymers

Two typical fractionation curves of the products from grafting reactions, in which the total percentage of polymer recovered is plotted as a function of the methanol content of the solution, are shown in Fig. 2, together with a

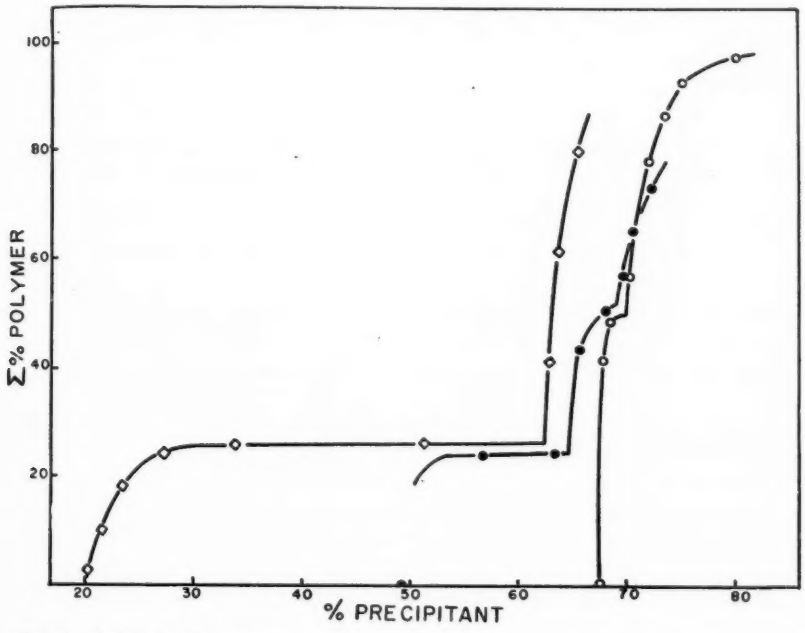

FIG. 2. Fractionation curves.
Expt. No. A1, –○–; Expt. No. E3, –●–; Synthetic mixture containing 26.9% of brominated polystyrene C, and 73.1% polymethyl methacrylate, –◇–.

curve of a synthetic mixture of brominated polystyrene and polymethyl methacrylate. The latter has been displaced five units to the left in the ordinate scale for clarity. The double inflection in experiment E3 was also observed in the fractionations of other graft copolymers with high degrees of branching.

Probably this initial coagulation represents a nonequilibrium condition resulting from the intertwining of branched polymer chains with the formation of aggregates. These first fractions were always precipitated as more highly swollen gels than later ones although the analysis values were the same. There is an alternative explanation. If, under the conditions of the branching reactions, a fraction of the growing branches terminate by a combination mechanism (2) some cross-linking will occur as the frequency of branching increases with the formation of molecules having two or three times the molecular weight of the average. As this would create a distinct discontinuity in the molecular weight distribution, the solubility curve would also be discontinuous. However, the comparatively crude fractionation method employed is not usually capable of separating molecular weight species of this order.

During the fractionation experiments, an interesting solubility phenomenon was observed. Within the solvent–precipitant range where polystyrene usually precipitates, the solutions became opaque although no coagulation and gel formation occurred. They were quite stable, could be kept for several days without change, and even centrifuging at moderate speeds (up to 5000 r.p.m.) only partly coagulated the suspended polymer. In this solubility range, it appears that the graft copolymer molecules behave in a manner somewhat analogous to a micelle. Presumably the precipitant causes desolvation of the polystyrene part of the molecule, with a partial collapse of the polymer segments, while the polymethyl methacrylate branches remain solvated and thus prevent coagulation. The same type of behavior was noted by Merrett (11) with copolymers composed of polymethyl methacrylate branches grafted onto rubber.

In Fig. 3, the methyl methacrylate compositions of the individual polymer fractions have been plotted as a function of their cumulative mean weight percentages for a series of experiments with increasing amounts of branching. The analyses of successive copolymer fractions remained sensibly constant except where the frequency of branching was small. The lower values in the first fractions of these examples may be due to contamination with small amounts of the initial brominated polystyrene which remained unbranched. As this material has a lower solubility than either the copolymer or polymethyl methacrylate, it will coprecipitate with the first fraction. That contamination is not a serious factor was demonstrated by a fractionation experiment with a synthetic mixture of graft copolymer and brominated polystyrene in which at least 90% of the latter was recovered. In addition, when the frequency of branching is low, the large solubility differences between molecules with consecutive numbers of branches may give a similar trend.

The fractionation experiments also provide an alternative method to infrared analysis of estimating the compositions of the copolymer samples. Assuming that the inflection point in a fractionation curve corresponds to the separation of graft and linear polymer, the composition can be determined from the total weight of graft copolymer and the corresponding weight of brominated polystyrene used as initiator. The agreement between the two methods is within the experimental accuracy (Table III). From the weight

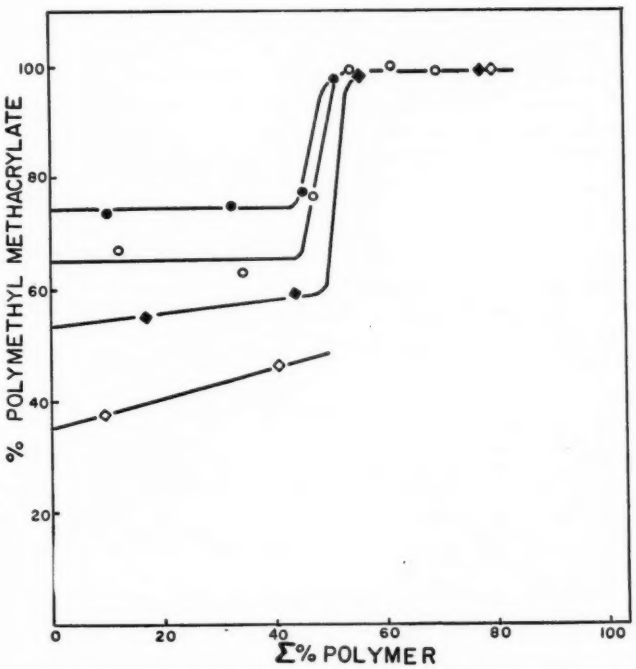

FIG. 3. Plot of polymethyl methacrylate composition versus total weight of polymer recovered.
Expt. No. E1, –◇–; Expt. No. E2, –◆–; Expt. No. E3, –○–; Expt. No. E4, –●–.

TABLE III

GRAFT COPOLYMERS OF STYRENE AND METHYL METHACRYLATE

Expt. No.	% PMMA (fractionation)	% PMMA (infrared)	$\bar{P}_n$ (styrene backbone)	$\bar{P}_n$ (methacrylate branches)	Monomer units of backbone per branch	Average no. of branches per molecule
A1	64	67	2500	4500	2100	1.2
A2	49	47	2500	1500	1700	1.5
D1	63	66	3100	2300	1200	2.6
D2	65	65	3100	1700	900	3.4
D3	62	60	3100	1600	1000	3.0
D4	59	58	3100	1300	920	3.3
E1	41	41	3800	1500	2100	1.8
E2	57	55	3800	1500	1200	3.2
E3	68	64	3800	1800	950	3.9
E4	75	74	3800	1900	650	5.9

fraction of the branches and their average chain length, a simple calculation yields the frequency of branching. The complete data for a number of graft copolymers are given in Table III. The copolymer compositions determined by infrared analysis were used in the calculations as these were considered

more reliable. In the series of experiments E1–E4, the polymerization conditions were kept constant and increasing amounts of branching were obtained by allowing the reactions to go to progressively higher conversions. Because of the decrease in polymerization rate with extent of reaction, there is also a small increase in the chain lengths of the branches for the series.

The methods that have been described for the synthesis and characterization of graft copolymers of styrene and methyl methacrylate should be of general applicability.

ACKNOWLEDGMENTS

The author is indebted to Miss E. Kirby for the infrared analyses and to Mr. S. Wasniewski for technical assistance. The microanalyses were made by the Microtech Laboratories, Skokie, Illinois.

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MOLECULAR INTERACTION OF HYDROGEN CHLORIDE WITH π-ORBITAL DONOR MOLECULES

I. ALKENES AND ALKYNES[1]

By D. Cook,[2] Y. Lupien, and W. G. Schneider

ABSTRACT

Hydrogen chloride, which is a convenient small molecule "acceptor", was used to study the donor capacity of π-orbitals in a number of ethylenic and acetylenic hydrocarbons. The composition of the molecular addition compounds formed between these hydrocarbons and hydrogen chloride was determined by thermal analysis. The freezing-point diagrams for hydrogen chloride with a number of lower alkene homologues and with several alkyne homologues are reported. The addition compounds formed by the alkenes have HCl:hydrocarbon molecular ratios of 1:1 and 2:1. An exception is 2-methyl-butene-2 which undergoes rapid chemical reaction with HCl even at low temperatures. The HCl-complexes formed by the alkynes have molecular ratios 1:1, 2:1, and 4:1. Addition compounds of this type are not formed by the saturated hydrocarbons ethane and propane and therefore they must be attributed to specific forces of interaction of HCl with π-orbitals of the unsaturated hydrocarbons. It is suggested that weak hydrogen bonds are formed between the acid acceptor and the donor π-orbitals. To account for the 2:1 complex in the alkenes and the 4:1 complex in the alkynes it is necessary to postulate that each π-orbital can accommodate two molecules of HCl.

INTRODUCTION

Molecules containing either lone pair orbitals or π-orbitals frequently have a highly directed intermolecular force field and may accordingly associate or form molecular complexes with other molecules. Generally speaking, a lone pair orbital is localized on one atom of the molecule from which it projects out into space as a well-defined region of negative charge. Accordingly such molecules are usually polar and they are good electron donors capable of complex formation with an acidic or acceptor molecule. A common example of complexes of this type is the hydrogen bond. A π-orbital, on the other hand, while it also represents a directed region of negative charge on the molecule, is usually not as well localized and consequently does not project out as far from an atom center as a lone pair orbital. Moreover because of its symmetry a π-orbital does not impart a "polar" character to the molecule. Nevertheless one should expect π-orbitals to have a definite, although weaker, donor property and hence to be capable of forming a variety of molecular complexes, including perhaps a weak hydrogen bond.

In this connection it was of some interest to study the donor capacity of the π-orbitals in olefins and acetylenic compounds. The technique employed for this purpose was that of thermal analysis. In order to ascertain what molecular complexes these hydrocarbon molecules form with a simple acceptor (acid) molecule like hydrogen chloride the freezing-point diagram of the binary

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Contribution from the Division of Pure Chemistry, National Research Laboratories, Ottawa, Canada. Issued as N.R.C. No. 5083.
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mixture was determined. For this purpose hydrogen chloride may be regarded as a "probe" molecule. It is a small molecule and a strong acceptor and hence we may assume that if we add sufficient hydrogen chloride (and if the temperature is not too high) all the donor centers of a given molecule will be saturated. Thus, one may expect that the molecular compound appearing in the freezing-point diagram with the greatest hydrogen chloride content will give an indication of the maximum number of active donor centers in a given molecule. The use of hydrogen chloride as a test molecule has a further advantage. Some of the molecular complexes may be expected to be weak. Since hydrogen chloride has a low melting point it is possible to work at low temperatures, and under these conditions even weak complexes may be expected to show up in the freezing-point diagram.

EXPERIMENTAL

The freezing-point cell employed in the present work was similar to that used previously (2). It was joined to a high vacuum system in which known amounts of pure dry hydrogen chloride gas could be measured volumetrically and subsequently condensed into the freezing-point cell cooled with liquid nitrogen. The amount of hydrocarbon in each mixture was obtained either by volumetric measurement or, in the case of liquid hydrocarbons, by weighing from a weighing bulb which could be attached to the vacuum system. The hydrocarbons employed were Phillips "Research Grade" chemicals. Temperatures were measured with a copper–constantan thermocouple. Cooling curves were recorded with a Leeds and Northrup "Speedomax" recorder.

RESULTS

The freezing-point diagrams of hydrogen chloride with some simple alkenes are shown in Fig. 1 and those with some alkynes in Fig. 2. In these diagrams vertical dotted lines indicate the composition of the molecular compounds formed, horizontal dotted lines are eutectic lines, and curved dotted lines are the hypothetical melting curves of incongruently melting compounds. Duplicate cooling curves were obtained for each mixture and each composition was repeated with a fresh mixture. The melting points were reproducible to $\pm 1.0°C.$, the estimated accuracy of the measurements.

The compositions and melting points of the molecular compounds formed are summarized in Table I. Ethylene, propylene, and *cis*-butene have similar freezing-point diagrams in that they all show two compounds containing one and two molecules of HCl respectively, per molecule of olefin. In this respect *trans*-butene appears somewhat anomalous in that, while a 2:1 compound (two molecules of HCl per molecule of olefin) is present, the 1:1 compound is not evident. Actually the absence or presence of the latter compound in the HCl–*trans*-butene system may be somewhat doubtful. If it does exist it would be expected to melt incongruently because of the high melting point of *trans*-butene itself. Moreover, mixtures of *trans*-butene (as well as *cis*-butene) with HCl showed a marked tendency to supercooling and glass formation which was

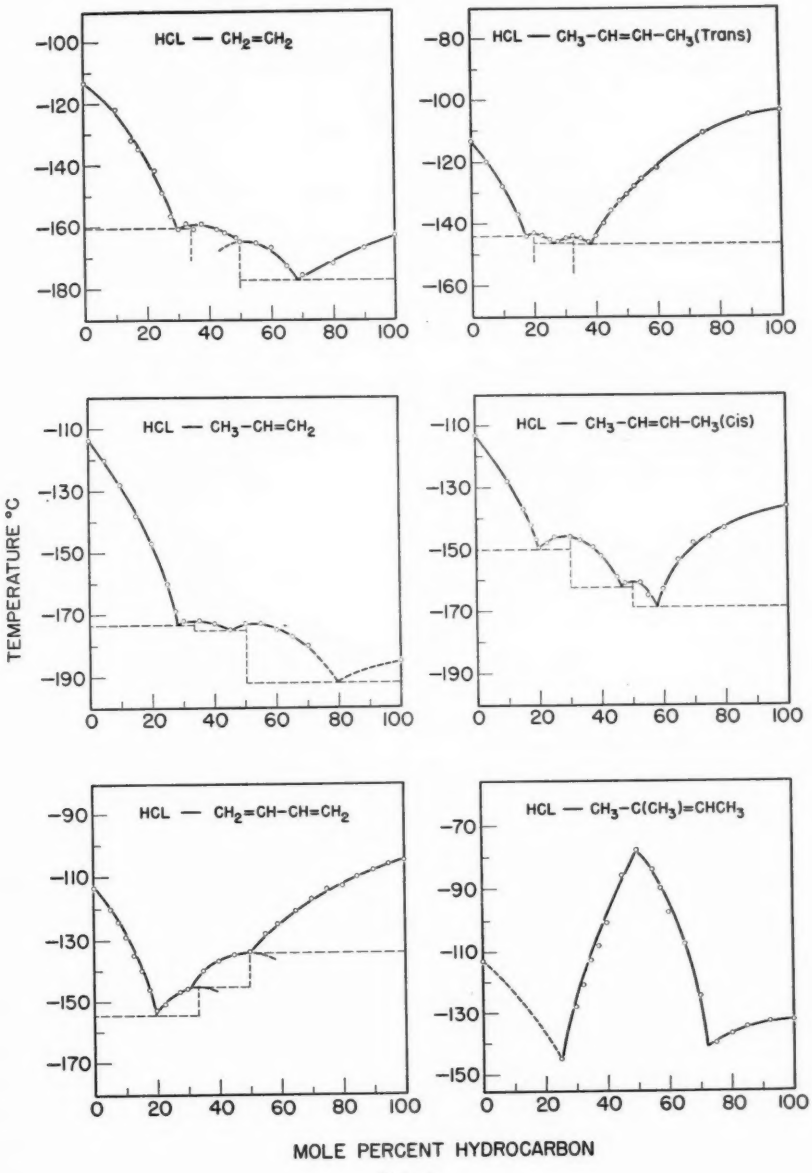

FIG. 1.

particularly pronounced in mixtures containing between 50 to 80 mole per cent of hydrocarbon. Consequently the freezing-point diagram in this composition range has a somewhat greater uncertainty. *trans*-Butene also differs from the

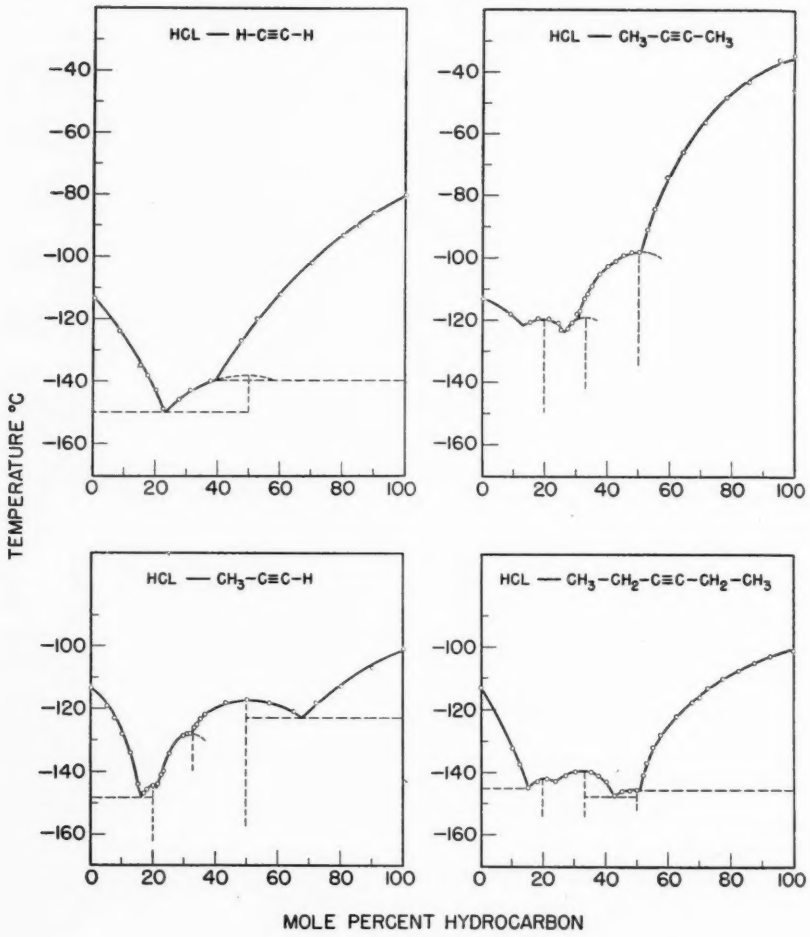

FIG. 2.

other three olefins in that an additional compound with composition 4:1 appears in the freezing-point diagram.

The freezing-point diagram of 2-methyl-butene-2 is strikingly different from the above-mentioned olefins. It shows a very pronounced (stable) 1:1 compound. This type of diagram results when instead of molecular compound formation a chemical compound is formed. Chemical addition of HCl across the double bond was verified by measuring the proton magnetic resonance spectrum of the product, 2-methyl-2-chloro-butane, and comparing this with the spectrum of the parent olefin. It is curious why HCl addition, which appears to be almost instantaneous, takes place so readily for this particular

TABLE I

SUMMARY OF HYDROGEN CHLORIDE MOLECULAR COMPOUNDS

Hydrocarbon	Compound, HCl:hydrocarbon	Melting point* (°C.)
Ethylene	1:1	−165
	2:1	−159
Propylene	1:1	−172
	2:1	−173
cis-Butene-2	1:1	−160
	2:1	−145
trans-Butene-2	2:1	−143
	4:1	−139
Butadiene	1:1	−135
	2:1	−145 (*i*)
Acetylene	1:1	−137 (*i*)
Propyne	1:1	−117
	2:1	−128 (*i*)
	4:1	−145
Butyne-2	1:1	− 98
	2:1	−120 (*i*)
	4:1	−119
Hexyne-3	1:1	−145
	2:1	−139
	4:1	−142

*(*i*)—*Incongruent melting point.*

olefin at temperatures below −60°C. In an attempt to eliminate possible impurities which might serve as catalysts, another sample of 2-methyl-butene-2 was distilled through an efficient fractionating column. This sample yielded identical results.

In the freezing-point diagrams for the alkynes with HCl, propyne, butyne-2, and hexyne-3 all have similar diagrams in that the compounds 1:1, 2:1, and 4:1 appear. The first member of this series, acetylene, is anomalous, forming only a 1:1 compound.

From the above results the conclusion emerges that all the unsaturated hydrocarbons studied, with the exception of 2-methyl-butene-2, form molecular complexes with hydrogen chloride. If this is a specific property of hydrocarbons containing a π-orbital it should be absent in the saturated hydrocarbons. To test this the freezing-point diagram for the propane–HCl system was determined. This is shown in Fig. 3. The freezing-point diagram of the ethane–HCl system has been previously reported in the literature (1). The phase diagrams for these two systems are similar in that they exhibit neither eutectic points nor molecular compounds. The diagrams are consistent with the assumption that the solid phase consists of a continuous series of solid solutions.

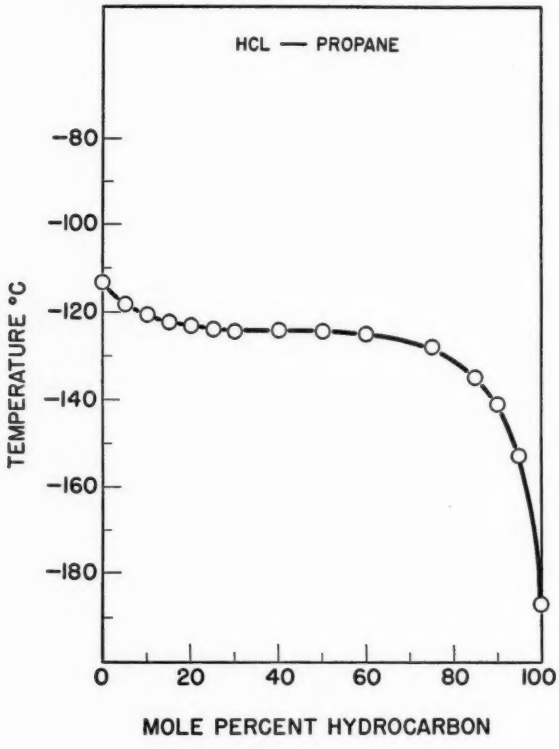

FIG. 3.

DISCUSSION

From an inspection of the molecular compounds which appear in the phase diagrams of the olefins and acetylenic compounds with HCl the following striking pattern emerges: In the olefin systems the compositions of the molecular compounds which predominate have HCl to hydrocarbon ratios of 1:1 and 2:1; for the alkynes the compounds with composition 1:1, 2:1, and 4:1 predominate. The deviations from this pattern which occur have already been mentioned. Since the same addition compounds appear for each hydrocarbon of a homologous series irrespective of the size and shape of the hydrocarbon molecule, this suggests that the compounds are in the main not due to geometrical considerations of crystal packing, but that they must be attributed to specific forces of interaction between HCl and the unsaturated hydrocarbons. This is also confirmed by the fact that the saturated hydrocarbons, ethane and propane, form no addition compounds with HCl.

The specific forces operative may be assumed to be of the donor–acceptor type in which HCl, which interacts only weakly with itself, functions as the acid acceptor. The donor centers must then be presumed to be the π-orbital

of the unsaturated hydrocarbon. Hence in the addition compound the H atom of the hydrogen chloride is directed toward a lobe of the π-orbital. This is in effect a weak hydrogen bond. Such hydrogen bonds may be expected to be weaker than ordinary hydrogen bonds involving n-donors since π-orbitals are not as well localized as lone pair orbitals (3). Moreover if the assumption is made that each ethylenic-type π-orbital can accommodate a maximum of two HCl acceptors, one on each lobe of the π-orbital, then the composition of the addition compounds appearing in the freezing-point diagrams can be accounted for. Thus the olefins may complex with one or two molecules of HCl per molecule of hydrocarbon, while the alkynes, under favorable conditions, may accommodate up to four molecules of HCl. A similar explanation has been advanced previously (2) to account for the observed addition compounds of HCl with alkyl nitriles.

Two of the hydrocarbons studied apparently do not exhibit their maximum donor capacity relative to HCl. These are butadiene and acetylene, each of which contains two π-orbitals, and they might therefore be expected to form addition compounds containing a maximum of four HCl molecules. The π-orbitals in butadiene and other conjugated diolefins are known to be more delocalized than those of ethylene and therefore could be weaker donors. Acetylene, the first member of the alkyne series, is also a weak donor (weak base). This is indicated by its rather high ionization potential* relative to that of the higher homologues of the alkyne series and to that of ethylene.

The HCl-complexes of all the unsaturated hydrocarbons studied are relatively weak. This is evident from the general nature of the phase diagrams, the fusion curves of the addition compounds exhibiting broad, flat maxima. It is quite possible that in many cases the compounds are relatively stable only at low temperatures.

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**The ionization potential can frequently be used to give a rough correlation of donor strengths of a series of compounds; the lower the ionization potential the greater the donor or basic strength.*

MOLECULAR INTERACTION OF HYDROGEN CHLORIDE WITH π-ORBITAL DONOR MOLECULES

II. BENZENE AND METHYL BENZENES[1]

By D. Cook,[2] Y. Lupien, and W. G. Schneider

ABSTRACT

Freezing-point diagrams of the binary systems consisting of hydrogen chloride with each of the hydrocarbons benzene, toluene, *o*-xylene, *m*-xylene, *p*-xylene, and mesitylene were determined. The phase diagrams exhibit 1:1 complexes in each of these systems. Toluene shows an exceptional behavior in that an additional compound containing two molecules of hydrocarbon per molecule of hydrogen chloride is also formed. The 1:1 complexes are attributed to weak hydrogen bonds formed between the acid and the π-orbital donors of the hydrocarbon. Colored complexes with HCl are formed by *trans*-stilbene and anthracene. The saturated cyclic hydrocarbons cyclohexane and cyclopropane form no addition compounds with hydrogen chloride.

INTRODUCTION

The methods described in the previous paper (3) were employed to study the π-orbital donor capacity of some benzene hydrocarbons. The binary phase diagrams of hydrogen chloride with benzene, toluene, ortho-, meta-, and para-xylene, and mesitylene are shown in Fig. 1. As in the previous paper, vertical dotted lines represent the composition of the complexes formed, horizontal dotted lines being the eutectic lines. Curved dotted lines represent the hypothetical melting lines of incongruently melting complexes. As a direct result of the high melting points of benzene and *p*-xylene relative to that of HCl, these hydrocarbons form incongruently melting complexes whose composition cannot be definitely established. It is very probable, however, that the molecular ratio of HCl to hydrocarbon in the complex is 1:1, since complexes of this composition appear in all the other systems studied. Toluene exhibits a somewhat anomalous behavior. In addition to a 1:1 complex, there is a further compound containing two molecules of toluene per molecule of HCl. Table I contains a summary of the melting points of the complexes appearing in the phase diagrams.

Addition products, presumably 1:1 complexes, were also indicated for *trans*-stilbene and anthracene with HCl. Small amounts of these hydrocarbons were dissolved in anhydrous liquid HCl. *trans*-Stilbene yielded a deep blue solution and anthracene a yellow solution. Because of the high melting points of these hydrocarbons the complete phase diagram for these mixtures could not be measured with the apparatus employed for the present experiments. Such measurements could no doubt be carried out with a suitable high pressure freezing-point cell.

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Contribution from the Division of Pure Chemistry, National Research Laboratories, Ottawa, Canada. Issued as N.R.C. No. 3984.
[2]*National Research Laboratories Postdoctorate Fellow 1953–55. Present address: Dow Chemical Company, Midland, Michigan.*

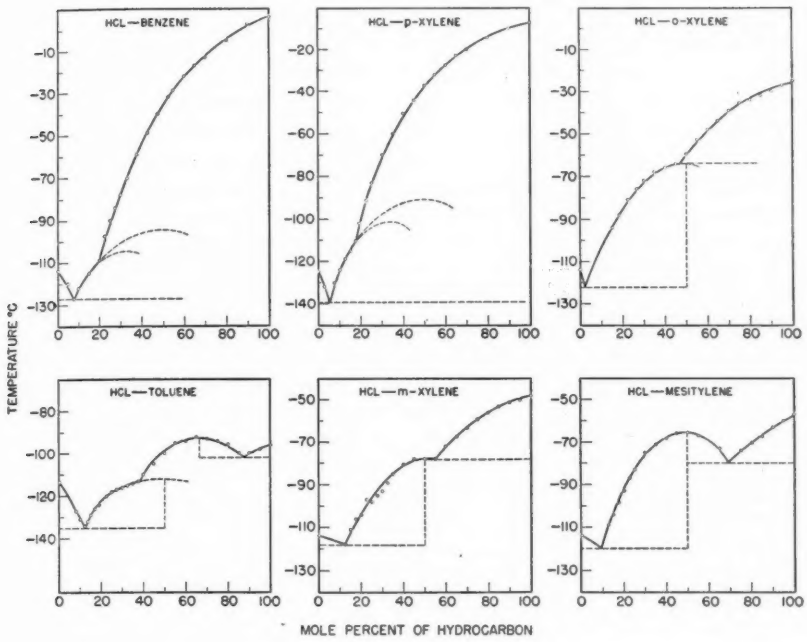

FIG. 1.

TABLE I

SUMMARY OF HYDROGEN CHLORIDE COMPLEXES

Hydrocarbon	Compound, HCl:hydrocarbon	Melting point* (°C.)	Color of complex
Benzene	1:1	−110 (*i*)	Colorless
Toluene	1:1	−112 (*i*)	"
	1:2	− 91	
o-Xylene	1:1	− 64	"
m-Xylene	1:1	− 78	"
p-Xylene	1:1	− 93 (*i*)	"
Mesitylene	1:1	− 66	"
trans-Stilbene	(1:1)		Blue
Anthracene	(1:1)		Yellow

*(*i*)—*Incongruent melting point.*

The phase diagrams of two cyclic saturated hydrocarbons, cyclopropane and cyclohexane, with hydrogen chloride were also determined (Figs. 2*a* and 2*b*). The HCl–cyclohexane system exhibits neither an addition compound nor a eutectic. In this respect the diagram is similar to that of the ethane–HCl and propane–HCl systems. The corresponding diagram for the cyclopropane–HCl system shows only a eutectic point.

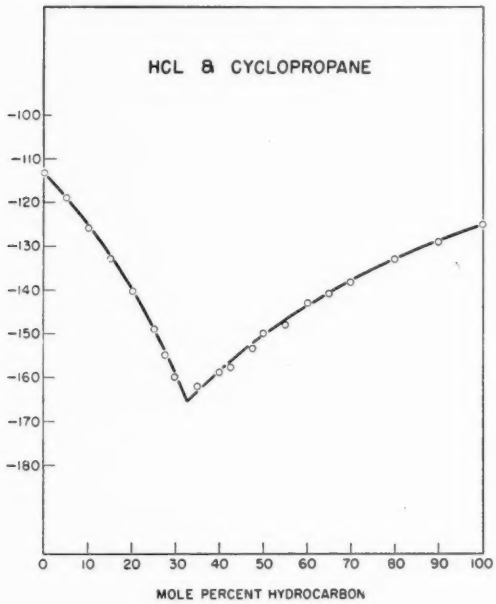
HCL & CYCLOPROPANE
-100
-110
-120
-130
-140
-150
-160
-170
-180
0
10
20
30
40
50
60
70
80
90
100
MOLE PERCENT HYDROCARBON

FIG. 2*a*.

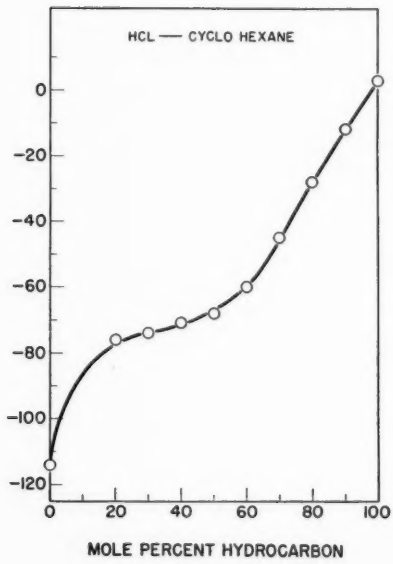
HCL — CYCLO HEXANE
0
-20
-40
-60
-80
-100
-120
0
20
40
60
80
100
MOLE PERCENT HYDROCARBON

FIG. 2*b*.

DISCUSSION OF RESULTS

In contrast to the HCl complexes of the olefins and acetylenic hydrocarbons which give rise to several complexes differing in their HCl content, the benzene hydrocarbons form mainly only a 1:1 complex. Toluene, which also gives rise to a 1:2 complex, appears to be an exception to this behavior. Since the saturated cyclic hydrocarbons cyclohexane and cyclopropane do not undergo complex formation with HCl, it must be concluded that, as in the case of the alkenes and alkynes, specific forces of interaction exist between the π-orbitals of the aromatic molecules functioning as donors and the acceptor hydrogen chloride. Since the π-orbitals of the aromatic molecules are much more delocalized than those of the alkene or alkyne molecules, their basic strength may be somewhat weaker and this may contribute to the fact that 1:1 HCl complexes predominate in the former. However this cannot be a complete explanation as other factors, such as the greater polarizability of the aromatic π-orbitals, undoubtedly play a part.

In the complex it appears reasonable to assume that the HCl molecule is oriented with its molecular axis approximately at right angles to the plane of the aromatic molecule and with the hydrogen end directed toward a π-orbital, i.e. toward a carbon atom or a carbon–carbon bond. A further question of interest is whether or not the 1:1 complex exists in the form of discreet dimers, i.e. HCl plus hydrocarbon, which was assumed to be the case for the alkene and alkyne complexes, or whether it forms a repeating chain-like structure.* The latter may be expected to occur if the Cl atom of HCl is capable of interacting with the π-orbitals of a second hydrocarbon molecule, permitting the structure to repeat itself. It is known, for example, that the halogen atoms of alkyl halides interact appreciably with π-orbitals (5) as do also the halogen molecules chlorine, bromine, and iodine.

The anomalous 1:2 HCl–toluene complex is apparently not of the above type. A possible structure, which could account for the observed molecular ratio, is one in which the toluene molecules occur in pairs with their molecular planes parallel and the methyl groups at opposite ends to minimize their mutual repulsion. The pairs could then form a 1:1 complex with HCl. Such a structure, which is entirely speculative, could conceivably be dictated by economy of crystal packing. It is of interest to note that the hydrogen bromide – ethyl benzene system, which was investigated by Maass and Russell (4), also exhibits both a 1:1 and 1:2 compound. These authors also observed a 1:2 compound in the HBr–toluene system but not a 1:1 compound. However, the freezing-point diagrams for the HBr–benzene and HBr–mesitylene systems closely parallel the present results with hydrogen chloride.

The general nature of the freezing-point diagrams indicates the HCl–mesitylene complex to be the most stable and that of ortho- and meta-xylene to be more stable than the complexes of toluene or benzene. Although this is an extremely rough correlation it is also the order of basicity (donor strength)

**It now appears likely that the complexes of chlorine, bromine, or iodine with benzene or the methyl benzenes form chain structures in which the halogen molecule and the hydrocarbon alternate, the axis of the halogen being at right angles to the planes of the hydrocarbon (see J. Collin and L. d'Or. J. Chem. Phys. 23: 397. 1955).*

of these hydrocarbons established by studies of the corresponding iodine complexes (1) and indicated by their relative ionization potentials. A similar correlation of basic strengths has also been reported by Brown and Brady (2). These authors determined the relative solubility of hydrogen chloride in dilute solutions of aromatic hydrocarbons in toluene and in *n*-heptane. Increasing solubility of hydrogen chloride in the dilute solutions was observed in the order: benzene < toluene < *m*-xylene < mesitylene. The solubility results were explained on the basis of π-complex formation of the hydrogen chloride with the π-electrons of the aromatic hydrocarbons.

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THE HYDROLYSIS OF THE CONDENSED PHOSPHATES

III. SODIUM TETRAMETAPHOSPHATE AND SODIUM TETRAPHOSPHATE[1]

By Joan Crowther and A. E. R. Westman

ABSTRACT

The rates of hydrolysis of sodium tetrametaphosphate and tetraphosphate* (in the presence of tetrametaphosphate) have been measured at 65.5°C. over the pH range 2.5 to 13.3. Tetrametaphosphate anions hydrolyze to tetraphosphate which in turn hydrolyzes to triphosphate* and orthophosphate and not to pyrophosphate. Thus the terminal oxygen bridges in the tetraphosphate and not the central one are attacked preferentially. The reactions were first order and acid catalyzed. The tetrametaphosphate hydrolysis was also base catalyzed with a minimum rate in solutions of pH approximately 7.5. The rate of hydrolysis of tetraphosphate was greater than triphosphate at the hydrogen ion concentrations studied. Hydrolysis of a sodium phosphate glass indicated that preferential attack on terminal oxygen bridges takes place also with higher polymers. However, trimetaphosphate is formed at the same time.

INTRODUCTION

Although it is known that both the cyclic polymer tetrametaphosphate and the linear polymer tetraphosphate hydrolyze to form orthophosphate as a final product, little information has been published about their rates or reaction equations. The hydrolysis of tetraphosphate is particularly interesting since this is the lowest in the series of linear phosphates which has more than one mode of attack by a water molecule. If only the middle oxygen bridge is attacked, two moles of pyrophosphate are formed initially; if only an end bridge is attacked, one mole each of triphosphate and orthophosphate are produced; while uniform attack on all oxygen bridges would produce tri-, pyro-, and ortho-phosphate in equimolar amounts. Thus, a study of the hydrolysis of tetraphosphate should increase our knowledge of the properties of phosphate polymers.

The published work on the hydrolysis of tetra- and tetrameta-phosphate is limited and generally inconclusive. Bell, Audrieth, and Hill (1) have examined the hydrolysis of tetrametaphosphate. Their results agree qualitatively with those published in this paper if it is assumed that their analytical procedure was not suitable for determining small quantities of tetraphosphate. By measuring tri-, pyro-, and ortho-phosphate, Rodionova and Khodakov (6) decided that tetrametaphosphate hydrolyzes to tetraphosphate which subsequently hydrolyzes to tri- and ortho-phosphate; the value of their conclusion, however, was limited by their inability to analyze for the compounds with four phosphorus atoms. Such (7) also found evidence by measuring orthophosphate that tetrametaphosphate formed tri- and ortho-phosphate on hydrolysis. On the other hand, Thilo (8) believed that tetraphosphate partially

[1]*Manuscript received March 12, 1956.*
Contribution from the Department of Chemistry, Ontario Research Foundation, Toronto 5, Ontario. Presented at the Annual Conference, The Chemical Institute of Canada, June, 1955.

**More specific names in terms of current commercial practice would be hexasodium tetrapolyphosphate and pentasodium tripolyphosphate for sodium tetraphosphate and sodium triphosphate respectively.*

hydrolyzed to form pyrophosphate. Also, Quimby (5) gives four pieces of evidence that "suggest that alkaline media tend to split the tetraphosphate ion into two pyrophosphate fractions" and one piece of evidence which favored end-group cleavage. The latter he attributed to the high temperature reached (92°C.).

In general, evidence based on crystallization or precipitation techniques applied to a solution of hydrolyzates is suspect, since the compound appearing in a primary phase is frequently not the major solute or may even not be present in the solution, particularly when only a small yield is obtained.

Thus the difficulties involved in the analyses have prevented workers from establishing the equations for these hydrolysis reactions, and no quantitative information is available about their rate constants.

In the present work, the analytical problem has not been completely solved,* but the chromatographic procedure (2) employed did permit the determination of all components with a precision of two to three per cent. It has been possible therefore to propose equations for the hydrolysis reactions and to estimate their first-order rate constants at specified hydrogen ion concentrations.

EXPERIMENTAL

Materials

Pure sodium tetrametaphosphate tetrahydrate, $(NaPO_3)_4.4H_2O$, supplied by Albright and Wilson Limited was used. No other phosphates were found in the material (2) and the phosphorus content corresponded to the above formula. The solution used in the experiments contained 0.242 at. wt. of phosphorus per liter—this concentration being suitable for analysis.

Pure tetraphosphate was unobtainable in sufficiently large quantities when this work was in progress and thus a phosphate mixture, in which tetraphosphate was the major component, was used. This mixture was obtained by heating sodium tetrametaphosphate $[(NaPO_3)_4.4H_2O]$, in sufficient normal sodium hydroxide to break the ring, for one hour at 65.5°C. The resultant solution was a mixture of tetra- and tetrameta- with small amounts of tri- and ortho-phosphate anions. After suitable dilution (0.17 at. wt. of phosphorus per liter) this solution was used as the starting material for the hydrolysis study of sodium tetraphosphate.

Procedure

Samples (50 ml.) of the phosphate solutions were adjusted to within 0.1 unit of the desired pH value by adding sodium hydroxide and/or hydrochloric acid solutions of concentration such that a few drops only were required. Since any residual sodium hydroxide would be neutralized in adjusting the pH to the lower values with hydrochloric acid, the solutions might be as much as 0.04 molar in sodium chloride. The solutions were then placed in a long narrow tube and heated in a water bath at 65.5±0.1°C. This temperature was selected

**This and subsequent remarks refer to the period (1954) during which most of this work was done. With techniques and materials now available (1956) errors can be kept within one per cent. A. E. R. W.*

so that results could be compared with previous work (3). The starting time was initially assumed to be the time at which the solutions were placed in the bath. Since both reactions studied were first order, zero time was later checked by plotting $\log(a_0-a)$ against time. No adjustments were required. The pH value of the solutions was then adjusted to the desired value and maintained within ± 0.1 unit (unless otherwise specified in the following text) by the addition of drops of hydrochloric acid and/or sodium hydroxide solutions. (The concentrations of these solutions varied from normal to tenth normal depending on the sensitivity of the pH range.) The pH values were measured with a glass electrode and a Leeds and Northrup pH meter. At measured time intervals, samples were withdrawn and spotted on filter-paper chromatograms within one minute. Further hydrolysis during the analysis was negligible.

In the hydrolysis studies at pH 9.8, the pH of the solutions was not controlled as accurately as indicated above. During the day, the solutions were maintained at 9.8 ± 0.1 pH but during the night the pH fell from 10.2 to values as low as 9.0. Although this situation was undesirable, the rates of hydrolysis of tetrameta- and tetra- are comparatively insensitive to pH in this region (Fig. 4). Lastly, no pH control was attempted for the study of the hydrolysis of tetrametaphosphate at pH 13 owing to the insensitivity of the pH meter in this range. Thus the pH of this solution decreased from 13.4 to 12.7 during the course of the experiment, and the results are tabulated (Table I) for the average value 13.

Analysis

The analyses were carried out using a procedure developed in these laboratories (2). The method involves the separation of the phosphate components by filter-paper chromatography followed by a colorimetric determination of the amount of phosphorus in each component.

The analytical procedure had a serious drawback. Although the five components could be separated by filter-paper chromatography, the chromatographic techniques were such that it could not be efficiently done every time. Since the samples change on standing, there was no opportunity to repeat an analysis. Thus the precision of the analyses varied from one to three per cent. This defect is most apparent in the study of the hydrolysis of tetrametaphosphate anions. Here the normal mixture had a large proportion of tetrametaphosphate and small amounts of the other components—the most difficult type of chromatographic separation. In one set of analyses (pH 2.50) the resolution on the chromatograms of pyro- and tri-phosphate was so poor that only their sum is quoted. Consequently, the rate constants for this pH are approximate only. Although the analyses were not as precise as desired, yet they can be considered reliable in another sense since most of them were checked by different chromatographic procedures.

Data

The hydrolysis of sodium tetrametaphosphate in solution was studied at 65.5 ± 0.1°C. at pH values of 2.50, 5.30, 9.8, and approximately 13 (initial 13.4, final 12.7). The solution concentration was 0.242 at. wt. of phosphorus

TABLE I

HYDROLYSIS OF TETRAMETAPHOSPHATE

pH	Reaction time, min.	Distribution of phosphorus (%)					First order rate constant (k) of tetrameta-, min.$^{-1}$	Average k, min.$^{-1}$
		Tetra-meta-	Tetra-	Tri-†	Pyro-	Ortho-		
2.50	0	100	0	0*		0		
	1223	90.8	0.5	4.3*		4.4	7.9×10^{-5}	
	1485	89.4	0	6.6*		4.0	7.5 "	
	2645	87.8	1.9	5.3*		5.0	4.9 "	
	2922	82.8	2.1	7.3*		7.8	6.4 "	
	3925	69.7	4.9	12.3*		13.1	9.2 "	
	4085	68.4	3.7	10.4*		17.5	9.3 "	
	5742	61.2	6.4	16.9*		15.5	8.5 "	7.7×10^{-5}
5.30	0	100	0	0	0	0		
	1355	94.9	0	5.1	0	0	Negligible	
	1840	100.4	0	−0.4	0	0	"	
	2795	101.5	0	−1.5	0	0	"	
	2910	101.5	0	−1.5	0	0	"	
	3240	101.0	0	−1.0	0	0	"	
	4235	97.1	0	2.9	0	0	"	
	4325	102.6	0	−2.6	0	0	"	
	4712	100.3	0	−0.3	0	0	"	
	5840	95.0	0	5.0	0	0	"	
	6141	100.0	0	0	0	0	"	Negligible
9.8	0	100	0	1.4	0	0		
	1383	99.3	0	0.7	0	0	5.3×10^{-6}	
	1500	97.8	0	2.2	0	0	15.0 "	
	1760	97.8	0	2.2	0	0	13.0 "	
	3228	98.1	0	1.9	0	0	5.9 "	
	4253	96.9	0	3.1	0	0	7.5 "	
	4680	96.0	0	4.0	0	0	8.7 "	
	5697	96.9	0	3.1	0	0	5.6 "	
	6114	97.2	0	2.8	0	0	4.7 "	8×10^{-6}
13.0	0	100	0	0	0	0		
	30	100.3	0	−0.3	0	0	Negative	
	60	99.5	0	0.5	0	0	0.9×10^{-4}	
	120	97.3	0.5	2.2	0	0	2.3 "	
	180	94.5	4.4	1.1	0	0	3.1 "	
	210	97.8	1.2	1.0	0	0	1.1 "	
	241	95.9	3.2	0.9	0	0	1.7 "	
	270	93.8	6.5	−0.3	0	0	2.4 "	1.9×10^{-4}

**The sum of per cent phosphorus found in form of pyro- and tri-phosphate.*

†In chromatograms for Table I, some tetrameta- trailed back to the tri- position. The analyses were calculated on the assumption that this was consistent. This accounts for the uncertainty in the tri- percentages reports. Techniques developed later eliminated this difficulty and were used for the analyses reported in Table II.

per liter. The phosphorus distributions of the solutions at various times are given in Table I.

The hydrolysis of sodium tetraphosphate – sodium tetrametaphosphate mixtures in solution was studied at 65.5±0.1°C. at pH values of 2.55, 5.35, 9.8, and 13.3. The solutions' concentration was 0.17 at. wt. of phosphorus per liter. The compositions of the solutions after various time intervals are given in Table II and are plotted in Figs. 1, 2, and 3 for pH values of 5.35, 9.8, and 13.3 respectively. In every case the values for zero time are based on four to eight separate analyses.

TABLE II

HYDROLYSIS OF TETRAPHOSPHATE

pH	Reaction time, min.	Distribution of phosphorus (%)					First order rate constant (k) of tetra-, min.$^{-1}$	Average k, min.$^{-1}$
		Tetra-meta-	Tetra-	Tri-	Pyro-	Ortho-		
2.55	0	32.4	62.4	3.8	0	1.3		
	120	32.9	50.6	9.1	1.7	5.7	1.8×10^{-3}	
	240	32.2	45.0	12.4	4.0	6.4	1.4 "	
	300	32.4	34.3	19.5	5.3	8.5	2.0 "	
	360	33.3	30.2	24.2	2.4	9.8	2.0 "	1.8×10^{-3}
5.35	0	39.1	57.7	3.2	0	0		
	398	37.4	41.9	12.7	0	8.1	$8.1^{*}\times10^{-4}$	
	1349	36.2	18.6	20.2	5.8	19.3	8.4* "	
	1838	35.8	12.3	17.9	7.4	26.6	8.4* "	
	2792	37.8	7.1	15.2	12.0	27.9	7.5 "	
	3260	38.5	6.7	12.0	14.2	28.6	7.6 "	
	4238	37.4	4.1	9.9	14.8	33.9	6.2 "	
	4560	36.8	2.6	9.1	14.8	36.7	6.8 "	
	4690	38.9	3.2	8.9	13.9	35.1	6.2 "	
	5685	39.7	2.4	6.2	13.9	37.8	5.6 "	8.3×10^{-4}
9.8	0	22.6	63.3	9.0	0	5.1		
	298	19.3	58.5	12.5	0	9.7	2.1×10^{-4}	
	1252	24.2	45.4	20.8	1.8	7.8	2.7 "	
	1452	25.2	42.0	22.0	1.6	9.2	2.8 "	
	1585	22.8	42.6	23.4	2.3	8.9	2.5 "	
	1715	23.2	41.3	21.6	2.2	11.7	2.5 "	
	2705	24.4	32.9	29.4	4.1	9.2	2.4 "	
	2880	25.1	27.4	29.2	4.4	13.9	2.9 "	
	3150	22.7	32.5	28.0	2.6	14.2	2.1 "	
	4140	22.3	22.7	35.3	3.2	16.5	2.5 "	
	4329	20.6	25.2	34.8	3.7	15.8	2.1 "	2.5×10^{-4}
13.3	0	34.0	60.7	4.6	0	0.8		
	155	27.2	60.0	9.8	0	3.0		
	410	15.9	68.8	9.2	1.9	4.2		
	1368	4.1	68.2	18.6	1.6	7.6		
	1850	3.2	55.5	30.0	2.0	9.3		
	2809	0	45.9	34.1	3.6	16.4		
	2990	0	44.4	37.0	2.4	16.2		
	3295	0	44.1	37.0	2.6	16.2		
	4246	0	34.9	36.8	5.6	22.7		
	4721	0	36.5	38.9	4.4	20.2		
	5683	0	16.0	55.5	5.5	23.0		
	5905	0	16.5	55.8	5.1	22.5		
	6145	0	22.3	50.0	5.9	21.8		2.5×10^{-4}†

**Only these figures were used to calculate the first order rate constant.*
†For tetrametaphosphate 1.8×10^{-3} min.$^{-1}$.

Calculations

(*a*) *Tetrametaphosphate Data from Table I*

When the data for the hydrolysis of tetrametaphosphate anions (Table I) were substituted in the general equation for a first-order reaction, the rate constants 8×10^{-5}, 6×10^{-6}, and 2×10^{-4} min.$^{-1}$ were obtained for solutions with pH values of 2.50, 9.8, and approximately 13, respectively. The degree of hydrolysis at pH 5.30 was negligible even after 100 hr., while at pH 9.8 it was so small ($k = 6\times10^{-6}$ min.$^{-1}$) that the apparent hydrolysis could be due to experimental error. The values of the rate constants for each time interval

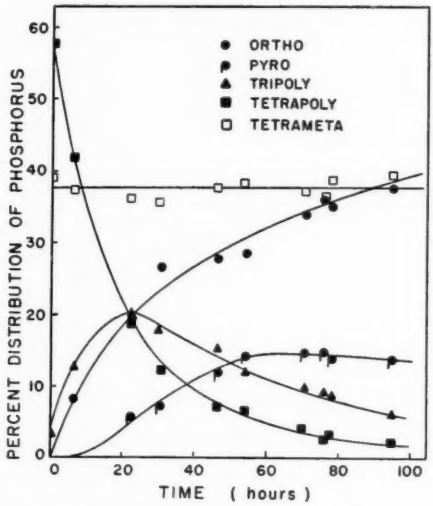


FIG. 1. Progress of hydrolysis, pH = 5.35.

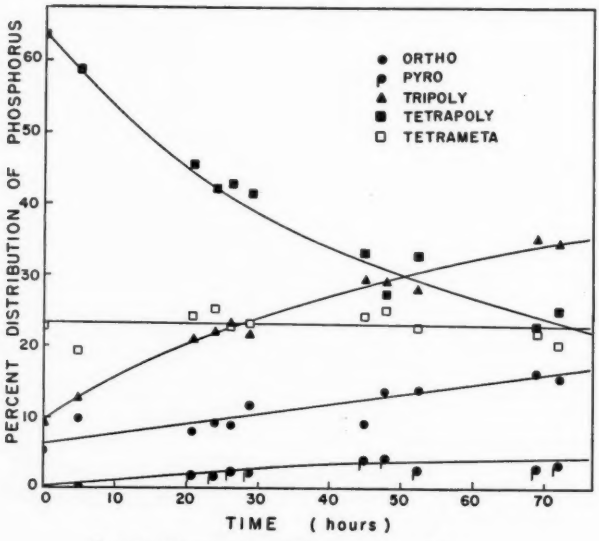


FIG. 2. Progress of hydrolysis, pH = 9.8.

measured from zero time are given in Table I along with the average values for each hydrogen ion concentration studied. The latter are plotted in Fig. 4 along with one value from Table II (pH 13.3) and with corresponding values for tri- and pyro-phosphate from Paper I (3) of this series. Within the limitations of the analytical methods, the data of Table I fit the equation for a first-order reaction, but more precise data might reveal departures from this.

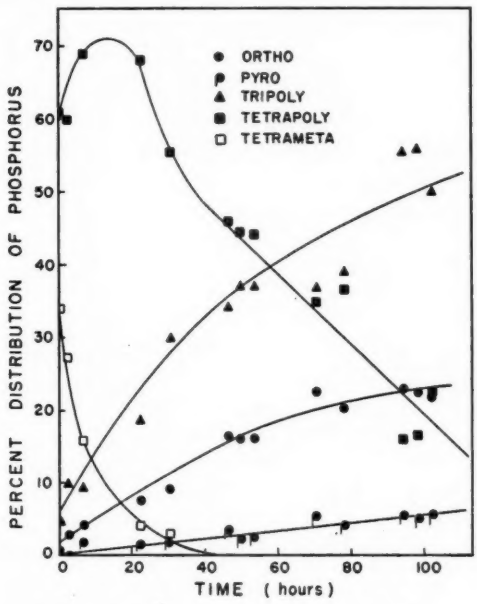


FIG. 3. Progress of hydrolysis, pH = 13.3.

(*b*) *Tetraphosphate Data from Table II*

The data for the hydrolysis of tetraphosphate anions in Table II fit the general equation for a first-order reaction for solutions with pH values of 2.55, 5.35, and 9.8. The values obtained for these first-order rate constants are included in Table II and plotted in Fig. 4. The standard first-order rate equation was used in these calculations since the rate of hydrolysis of tetrametaphosphate anions was so slow over this pH range that no effects from its decomposition were discernible; at pH 2.55 the experiment was limited to six hours to ensure this situation. These calculations, however, assume that the rate of hydrolysis of tetraphosphate is not affected by the presence of tetrametaphosphate.

At pH 13.3 the effects of the decomposition of tetrametaphosphate are evident, and the rate constants for both tetrametaphosphate and tetraphosphate anions were obtained from the equation (solved by approximation)

$$be^{k_1 t} = k_1 a_0 (1 - e^{-(k_2 - k_1) t}) / (k_2 - k_1) + b_0 e^{-(k_2 - k_1) t}$$

where a = fraction of total phosphorus atoms present in the form of tetrametaphosphate at time t,

b = fraction of total phosphorus atoms present in the form of tetraphosphate at time t,

a_0 = value of a at $t = 0$,

b_0 = value of b at $t = 0$,

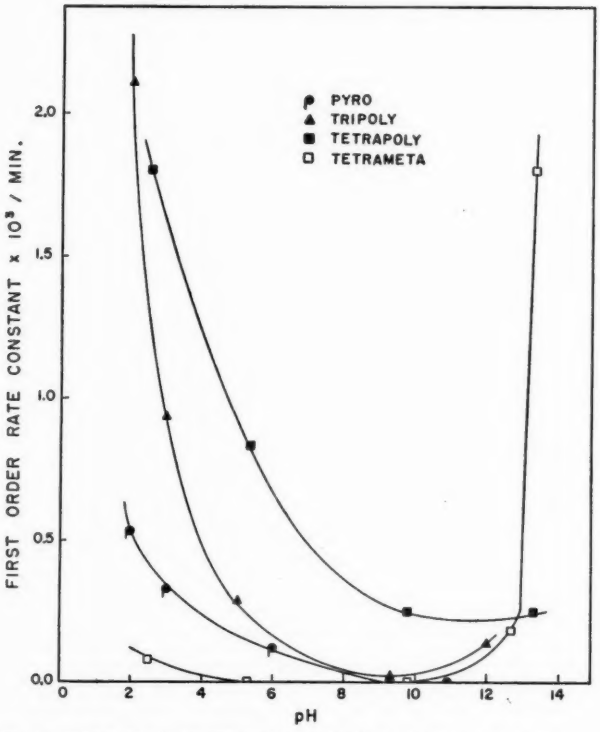


FIG. 4. Effect of pH on rates of hydrolysis of sodium phosphates.

k_1 = first-order rate constant for the hydrolysis of tetrametaphosphate anions,

k_2 = first-order rate constant for the hydrolysis of tetraphosphate anions.

This equation assumes that tetrametaphosphate hydrolyzes to tetraphosphate which in turn hydrolyzes, that both reactions are first order, and that these phosphates hydrolyze independently of each other. The justification of the first assumption is discussed in the following section. The values obtained for the rate constants were 1.8×10^{-3} min.$^{-1}$ and 2.5×10^{-4} min.$^{-1}$ for tetrameta- and tetra-phosphates respectively. This value for tetrametaphosphate is about 10 times that given for pH 13 in Table I. This is due to the fact that the rate of hydrolysis of tetrametaphosphate rises very abruptly in the neighborhood of pH 13 which is probably connected with the rapid rise in the concentration of sodium hydroxide required to reach pH values above pH 13.

When the pH of the solution is 5.35, the data for the hydrolysis of tetraphosphate anions do not fit the first-order equation after 85% of the tetraphosphate phosphorus is no longer in tetraphosphate form suggesting that deviations from first-order behavior may generally be expected in the final stages of this reaction.

DISCUSSION

(*a*) *Effect of pH*

The rate of hydrolysis of tetrametaphosphate anions (Table I and Fig. 4) is practically negligible over the range pH 5 to 10 but it increases at both ends of the scale.

The rate of hydrolysis of tetraphosphate anions, on the other hand, is effectively catalyzed by acid, but no increase in rate was observed over the pH range 7 to 13.3. This is surprising since tetraphosphate resembles chemically triphosphate and the latter shows such an increase (3), which Van Wazer has found to be a sodium ion effect (10). It is possible, of course, that the hydrolysis of tetraphosphate would show an acceleration if the alkalinity of the solution were further increased.

The great difference in rate between tetrameta- and tetra- in the region of pH 13.3 suggested a method for preparing solutions high in sodium tetraphosphate by hydrolysis of tetrameta-, which was readily available. When such a solution was converted to the ammonium form by ion exchange, concentrated (but not too far!) under vacuum, and allowed to stand at room temperature, plentiful crystals of ammonium tetraphosphate were obtained by P. A. Gartaganis in these laboratories. However, it was found that this work had been largely anticipated by Quimby (5), who prepared the more stable hexaguanidinium tetraphosphate.

In addition, the lead and barium tetraphosphates have been crystallized from melts by Langguth, Osterheld, and Karl-Kroupa (4). Thus, the earlier chromatographic evidence for the tetraphosphate ion (11) has been amply confirmed.

(*b*) *Reactions*

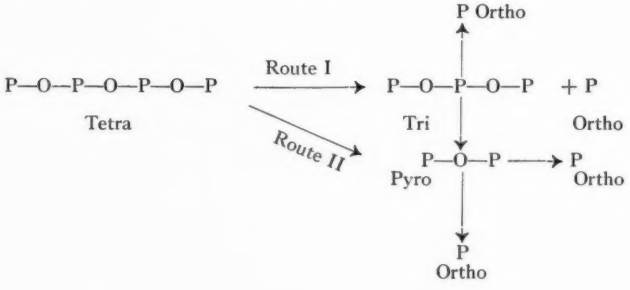
(*i*) *Tetrametaphosphate Hydrolysis*

At least some of the tetrametaphosphate must hydrolyze to tetraphosphate, since the latter is found whenever the rate of hydrolysis of tetrametaphosphate is appreciable (Table I, pH 2.5 and approximately 13). Over most of the pH range studied, the tetraphosphate hydrolyzed at a comparatively rapid rate (Table I vs. II and Fig. 4). Consequently, it cannot be established by inspection of the data that all tetrametaphosphate hydrolyzed to tetraphosphate, although there is a definite indication in the case of pH 13, Table I, where rate relations are more favorable.

In what follows, it is assumed that the tetrametaphosphate hydrolyzed first to tetraphosphate, i.e. the ring was not broken at two, three, or four oxygen bridges simultaneously to produce tri-, pyro-, or ortho-phosphate directly from the tetrametaphosphate. The best demonstration of this proposed reaction is given in Table II (data for pH 13.3) and Fig. 3. At this pH value, the rate of hydrolysis of tetraphosphate anions is less than that for tetrametaphosphate anions, and the proportion of phosphorus as tetraphosphate increases in the initial stages of the experiment owing to the hydrolysis of the cyclic phosphate.

(*ii*) *Tetraphosphate Hydrolysis*

As indicated earlier, the hydrolysis of tetraphosphate might proceed by two routes designated I and II in the following diagram where the phosphorus-oxygen skeletons are used to represent the ions concerned.



Route I involves attack on one end phosphorus–oxygen bridge exclusively; Route II on only the middle oxygen bridge. Inspection of Tables I and II and Figs. 1, 2, and 3 shows many cases in which the triphosphate content increases in unmistakable fashion to an extent that shows that Route I is at least the predominant route. In some cases, however, this effect is obscured to some extent by the rapid hydrolysis of the triphosphate and there is also the question as to whether one can say, within the limitations of the analytical method, that there is no direct hydrolysis to pyrophosphate, i.e. no attack on the middle oxygen bridge.

One method of examining this question by purely stoichiometric calculation, except for a small correction for initial tri- and pyro-, is illustrated in Table III. In this table, the data of Table II are corrected for the effect of the initial tri-, pyro-, and ortho- using the rate constants derived previously. The net increase in tri- at any time is multiplied by four-thirds to determine the minimum amount of phosphorus that has certainly gone by Route I according to the analysis. This is calculated as a percentage of the net phosphorus lost by (tetrameta- + tetra-) and reported in Column 7. The remainder of the phosphorus lost by (tetrameta- + tetra-) is then assigned to pyro- and ortho- by assuming Route I (Columns 8, 9), Route II (Columns 9, 10), and a negligible rate of pyro- hydrolysis. These calculated values may be compared with the corresponding observed values (Columns 6, 7).

At pH 9.8, the minimum percentage by Route I averages 86% and the remainder is distributed between pyro- and ortho- as expected if Route I is followed. Since the hydrolysis rate for pyro- at pH 9.8 is very slow, it may be concluded that the data do not lend any support to the hypothesis that any phosphorus follows Route II.

At pH 13.3, the minimum percentage by Route I averages 90%. The distribution of the remainder is not conclusive since it might have been obtained via Route I or II although the latter would require more hydrolysis of pyro-. There is an indication here that possibly pyro- is slightly base catalyzed.

TABLE III

STOICHIOMETRIC TEST FOR REACTION ROUTE

pH	Reaction time, min.	Analysis corrected for effect of initial tri-, pyro-, and ortho-					Minimum percentage by Route I, %	Distribution of remainder					
								Observed		Calculated by Route I		Calculated by Route II	
		Tetra-meta-	Tetra-	Tri-	Pyro-	Ortho-		Pyro-	Ortho-	Pyro-	Ortho-	Pyro-	Ortho-
2.55	0	34.2	65.8	0	0	0							
	120	34.7	53.4	6.0	1.5	4.5	66.6	1.48	2.53	2.60	1.30	3.90	0
	240	34.0	47.4	10.0	3.7	5.1	74.8	3.69	1.69	3.45	1.72	5.17	0
	300	34.2	36.2	17.5	5.0	7.3	79.0	4.96	1.37	4.15	2.08	6.23	0
	360	35.1	31.8	22.7	1.8	8.5	91.4	1.79	1.06	1.90	0.95	2.85	0
	Av.						77.0						
5.35	0	40.4	59.6	0	0	0	—						
	398	38.6	43.3	10.1	−0.2	8.3	74.9	−0.21	5.9	3.03	1.52	4.55	0
	1349	37.4	19.2	18.5	5.4	19.5	56.9	5.48	13.3	12.5	6.2	18.7	0
	1838	37.0	12.7	16.4	6.9	27.0	24.4	6.92	21.7	18.9	9.5	28.4	0
	2792	39.0	7.3	14.1	11.6	28.0	34.0	11.6	23.9	23.6	11.8	35.4	0
	3260	39.8	6.9	11.0	13.7	28.6	27.5	13.7	24.9	25.8	12.8	38.6	0
	4238	38.6	4.2	9.1	14.3	33.8	21.4	14.3	30.7	30.0	15.0	45.0	0
	4560	38.0	2.8	8.5	14.3	36.7	20.0	14.3	33.2	31.7	15.8	47.5	0
	4690	40.2	3.3	8.2	13.3	35.0	19.2	13.3	32.4	30.4	15.2	45.6	0
	5685	41.0	2.5	5.6	13.3	37.5	13.2	13.3	35.6	32.7	16.3	49.0	0
	Av.						32.4						
9.8	0	26.4	73.7	0	0	0	—						
	298	22.5	68.2	4.1	0	5.4	57.7	0	4.00	2.66	1.33	4.00	0
	1252	28.2	52.9	14.0	1.9	3.1	98.2	1.86	−1.52	0.23	0.12	0.35	0
	1452	29.4	49.0	15.4	1.6	4.8	94.2	1.63	−0.35	0.85	0.43	1.28	0
	1585	26.6	48.6	17.0	2.4	4.4	94.4	2.44	−1.12	0.88	0.44	1.33	0
	1715	27.0	48.1	14.9	2.3	7.7	79.7	2.33	2.72	3.36	1.68	5.05	0
	2705	28.4	38.4	24.2	4.3	4.8	97.0	4.31	−3.26	0.70	0.35	1.05	0
	2880	29.2	31.9	24.0	4.7	10.3	82.0	4.66	2.33	4.65	2.37	6.98	0
	3150	26.4	37.9	22.6	2.6	10.6	84.3	2.56	3.09	3.76	1.88	5.65	0
	4140	26.0	26.4	31.2	3.0	13.3	87.3	3.03	2.91	4.03	2.01	6.05	0
	4329	24.0	29.4	30.8	3.6	12.5	87.8	3.61	2.21	3.80	1.90	5.70	0
	Av.						86.3						
13.3	0	36.0	64.1	0	0	0	—						
	155	28.6	63.5	5.6	−0.1	2.3	95.5	−0.11	0.45	0.23	0.12	0.35	0
	410	16.8	72.8	5.2	1.8	3.5	66.0	1.80	1.76	2.37	1.19	3.56	0
	1368	4.3	72.0	15.8	1.1	6.9	89.2	1.06	1.58	1.69	0.85	2.54	0
	1565	0.3	61.9	24.6	1.2	7.2	100.0	1.16	−1.06	0	0	0	0
	1850	3.4	59.6	28.1	1.3	8.6	98.6	1.27	−0.74	0.35	0.18	0.53	0
	2809	0	48.5	33.0	2.6	15.9	85.5	2.64	4.86	5.00	2.51	7.51	0
	2990	0	47.0	36.0	1.3	15.6	70.7	1.27	3.6	3.31	1.65	4.96	0
	3295	0	46.6	36.2	1.5	15.6	90.5	1.48	3.6	3.38	1.69	5.07	0
	4246	0	36.9	36.4	4.3	22.3	77.0	4.34	10.15	9.66	4.84	14.5	0
	4721	0	38.6	38.8	3.0	19.7	84.3	2.96	6.66	6.40	3.21	9.61	0
	5683	0	16.9	56.7	3.9	22.4	91.0	3.91	3.49	5.00	2.50	7.50	0
	5905	0	17.4	57.0	3.5	21.9	92.3	2.49	2.86	4.30	2.15	6.45	0
	6145	0	23.6	51.0	4.2	21.2	89.3	4.23	4.01	5.50	2.75	8.25	0
	Av.						89.5						

At pH 5.35 the triphosphate and pyrophosphate are breaking down rapidly enough so that a purely stoichiometric test is not so conclusive. However, it will be observed that the triphosphate builds up before the pyrophosphate.

At pH 2.55 the reaction was not carried to the point where the triphosphate content starts to decrease. At least, triphosphate is the initial product.

Within the limitations of the analytical methods, therefore, it may be concluded that the hydrolysis of tetraphosphate occurs predominantly and quite probably exclusively by attack on an end oxygen–phosphorus bridge.

This may be a general rule for linear polyphosphates. In addition, it may be seen from Fig. 4 that the rate of hydrolysis for tetraphosphate is greater than that for triphosphate which, in turn, is greater than that for pyrophosphate. From this it could be expected that, if a polyphosphate glass having only medium length or longer polymers is used as a starting material in a hydrolysis experiment, the only low molecular weight phosphate formed initially should be orthophosphate and this could readily be determined by chromatographic or even chemical methods. Such an experiment was carried out later by P. A. Gartaganis of these laboratories. The data are given in Table IV. They show a

TABLE IV

HYDROLYSIS OF A PHOSPHATE GLASS
(pH = 3, 65.5°C., initial chain length = 17)

Weight per cent distribution of phosphorus	Time in minutes			
	0	295	625	1440
Ortho-	0.0	5.6	9.6	19.6
Pyro-	3.4	2.7	3.6	5.3
Tri-	7.5	4.5	5.5	6.2
Tetra-*	7.0	8.4	12.4	14.9
Penta-†	8.8	7.0	7.0	6.2
Hexa-	7.1	8.0	7.8	6.2
Hepta-	6.8	6.8	6.1	5.0
Octa-	5.4	6.0	5.2	4.5
Nona-	5.4	6.2	5.5	3.8
Hypoly-	48.6	44.7	37.3	28.2
	100.0	99.8	100.0	99.9

**Plus trimeta-.*
†Plus tetrameta-.

pronounced decrease in hypoly-, increase in ortho-, and increase in (tetra- + trimeta-). Chromatographing in other solvents showed that the last was due to a striking increase in trimeta-. Thus, two mechanisms were operating: (*a*) splitting off of end ortho- groups in all categories and (*b*) production of trimeta- from hypoly-. The latter accounts for about one-half the loss of hypoly-. Apparently, it was not accompanied by mid-chain breakage, so that something more detailed than the mechanism postulated by Thilo, Schulz, and Wichmann (9) may be necessary.

(*c*) *Independence*

The question as to whether each of the four condensed phosphates hydrolyzed in these experiments is hydrolyzed at a rate which is not affected by the other

phosphates present can be examined by means of the data given here. It involves the calculation of a number of chemically consecutive reactions occurring simultaneously and will be the subject of a later paper.

CONCLUSIONS

(*a*) *Order*

Tetrameta-, tetra-, tri-, and pyro-phosphate hydrolyze at constant pH by first-order kinetics for most of the course of the reaction.

(*b*) *Equations*

Tetrameta- hydrolyzes to tetra- which in turn hydrolyzes to tri- and ortho-. No evidence of a direct hydrolysis of tetra- to pyro- was found so that little if any attack occurs at the middle oxygen bridge in a tetraphosphate anion.

(*c*) *Rate Constants*

The rate constant for tetrameta- is very small except at very high pH values in the neighborhood of or above pH 13.

The rate constant for tetra- is greater than those for tri- and pyro- over the pH range studied, but shows no evidence of base catalysis at pH 13.3.

The progression from pyro- to tri- to tetra- is therefore not uniform as far as base catalysis is concerned but tetra- may be base catalyzed at higher alkalinities than those studied.

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THE CONVERSION OF HYODESOXYCHOLIC ACID TO PROGESTERONE[1]

By K. R. Bharucha, G. C. Buckley, C. K. Cross, L. J. Rubin, and P. Ziegler

ABSTRACT

A novel transformation of 3α,6α-dihydroxy steroids to their 3β-hydroxy-Δ^5 analogues was developed and applied to the preparation of progesterone from hyodesoxycholic acid.

Hyodesoxycholic acid was first isolated from hog bile by Windaus (17) who showed it to be a 3,6-dihydroxycholanic acid. The configurations of the two hydroxyl groups however were not elucidated until recently when they were assigned the α-positions (10). Since then this bile acid has not received a great deal of attention despite the fact that it represents a by-product of packing house operations. One of the reasons for this lack of interest has been undoubtedly the difficulty of its isolation from the crude animal bile, and only recently have adequate isolation procedures been worked out (2, 14). As a result, hyodesoxycholic acid is now a readily accessible material and it was the object of our work to utilize this bile acid for the preparation of physiologically active steroids.

Two major changes must be performed in order to convert methyl hyodesoxycholate (I*a*) to progesterone (XII). Firstly the side chain has to be degraded with loss of three carbon atoms and secondly the 3α,6α-dihydroxy grouping has to be transformed to the 3-keto-Δ^4 structure.

The side chain of I has previously been degraded by the classical Barbier-Wieland method to provide 3,6-dihydroxy-pregnan-20-one (7, 9). Later on, the procedure of Meystre and Miescher was applied to the same problem and resulted in greatly improved yields (6, 11). Our experiments were designed to improve this latter procedure, and at the same time the intermediate products were isolated and characterized. One of the modifications developed in the course of this work concerned the reaction of III*b* with N-bromosuccinimide which in the past was carried out in carbon tetrachloride with a light catalyst. This is hazardous on a large scale and also requires the installation of expensive equipment. It was found that a chemical free radical promoter such as diacetyl peroxide or α,α′-azo-diisobutyronitrile could be used instead of the light catalyst. The use of hydrocarbon solvents was found to be much superior to carbon tetrachloride since the brominated product was quite stable in hexane or commercial hydrocarbon mixtures in contrast to the chlorinated solvents. Various other modifications, of a minor nature, are described in the experimental section but it may be pointed out that these have significantly contributed to greatly enhanced yields (55% of VIII*a* from I*a*).

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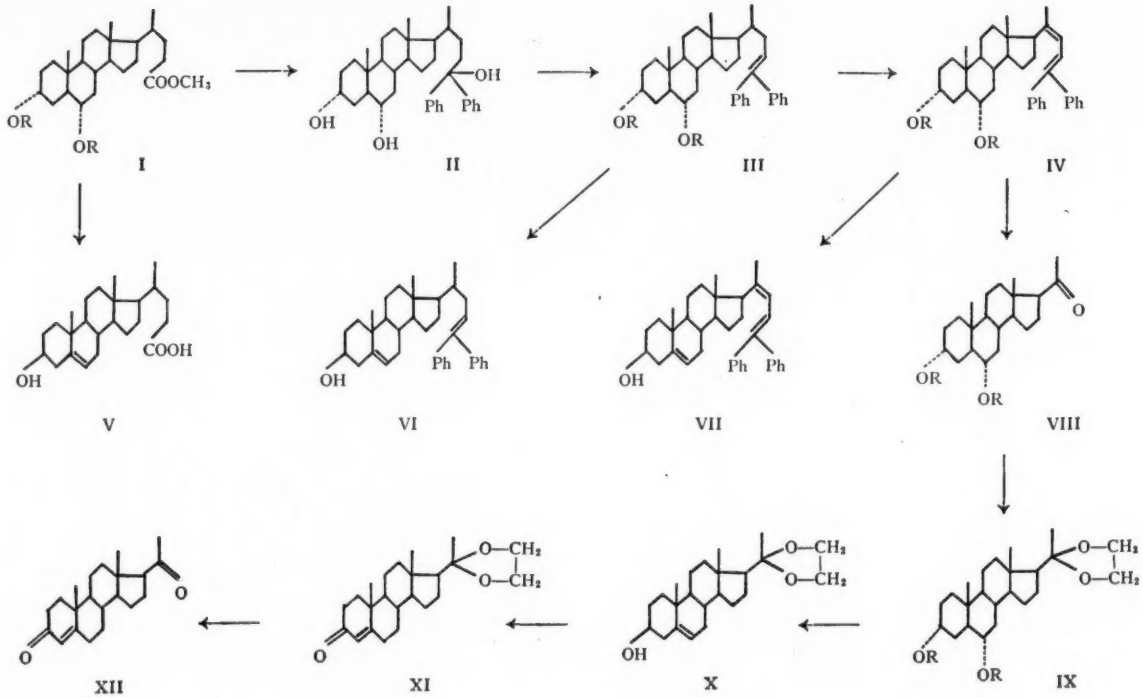
Contribution from the Research and Development Laboratories of Canada Packers Ltd., Toronto, Ont.



a, R = H *b*, R = Ac *c*, R = CH_2—C₆H₄—SO_2—

It then remained to develop a method whereby the 3α,6α-dihydroxy grouping could be converted in good yield to the 3-keto-Δ^4 analogue. The earliest attempts in this direction had been made by Marker (8, 9) who obtained progesterone by preferential hydrolysis of 3α,6α-diacetoxy-pregnan-20-one (VIII*b*) to the corresponding 3α-hydroxy-6α-acetoxy compound, followed by oxidation and dehydration. This was confirmed (4) when a small amount of 3-keto-6α-hydroxycholanic acid was isolated from I*b* by partial hydrolysis and subsequent oxidation. Several investigators then turned their attention to the use of preferential oxidations which would directly give 3-keto-6α-hydroxy steroids which in turn could be dehydrated readily. These oxidations were carried out by using Raney nickel with cyclohexanone (5, 6), aluminum tertiary butoxide and acetone (4), aluminum phenylate and acetone (5, 16), and N-bromosuccinimide in aqueous acetone (12, 13). Without exception the 3-keto-6-hydroxy derivative was accompanied by 3,6-diketo compounds and by unreacted starting material, and in most cases chromatography had to be resorted to in order to isolate the desired product. The 3-keto-6-hydroxy steroid was then transformed to the corresponding 3-keto-Δ^4 analogue by tosylation and dehydrotosylation (4, 5, 6) or by treatment with phosphorus oxychloride in pyridine (12, 13). Yamasaki (18, 19) then discovered that methyl hyodesoxycholate could be dehydrated to 3β-chloro-Δ^5-cholenic acid by the action of phosphorus oxychloride; treatment with potassium acetate, followed by saponification, provided 3β-hydroxy-Δ^5-cholenic acid. Two alternative methods for the preparation of 3β-acetoxy-Δ^5 steroids from the corresponding 3α,6α-ditosylates by treatment with silver acetate in acetic acid (1) or potassium acetate in acetic anhydride (15) have recently been reported. The yields are 30% and 45% respectively.

The approach that was used in our laboratories was similar to the methods referred to above (1, 15). We first tosylated methyl hyodesoxycholate to give quantitatively the corresponding ditosylate (I*c*). When the latter was refluxed with metal acetates in acetic acid it yielded, after saponification, 30% of V. When the dehydrotosylation was carried out in a neutral solvent such as acetic anhydride or aqueous acetone the yield of V increased to 50%. In these reactions there was invariably obtained a large amount of heteroannular dienes as shown by their ultraviolet absorption at 235 mμ. An improved procedure which we reported in an earlier note (20) employed a reaction medium of potassium acetate in aqueous dimethylformamide and in this way a marked increase in yield (70–75%) was achieved. The same results were obtained when N-methyl-pyrrolidone or N,N-dimethylacetamide was used. This method was then applied successfully to the products derived from the side-chain degradation of hyodesoxycholic acid and the desired 3β-hydroxy-Δ^5 steroids were isolated by crystallization. However, when 3α,6α-ditosyloxy-pregnan-20-one (VIII*c*) was treated accordingly the products had to be chromatographed to provide pure pregnenolone and besides the yield was lower than expected. This was due to the alkaline conditions prevailing during the dehydrotosylation reaction which probably cause racemization at C-17 of the steroid nucleus. To overcome this difficulty the keto group in VIII*a* was protected by formation

of the ethylene ketal IX*a*; the latter was then tosylated and dehydrotosylated in the usual manner, the 20-ketone group being regenerated by mild acid hydrolysis either before or after the Oppenauer oxidation. In this fashion progesterone was obtained from hyodesoxycholic acid in 30–35% yield.

During the dehydrotosylation of 3α,6α-ditosyloxy steroids, having a ring A/B *cis* junction, several reactions take place. There is an S_N2 mechanism operative at C-3 as evidenced by complete inversion at this location—a careful chromatography of the products failed to reveal any traces of the 3α-epimer. The formation of the double bond in ring B is due to an elimination reaction of the E1 type. As stated before there is always obtained a quantity of heteroannular diene which results from elimination both at C-6 and at C-3. It is interesting to observe that as the reaction medium is changed from acetic acid to acetic anhydride to aqueous dimethylformamide, the amount of 3β-hydroxy-Δ^5 steroid increases while the yield of diene decreases. The ratio of these products depends entirely on the relative rates of substitution and elimination. Since the 3α-tosyloxy group in compounds such as I*c* is equatorial and therefore not inclined to ionic elimination, the S_N2 mechanism at C-3 prevails as long as ring B remains saturated. If, however, elimination at C-6 is the first event leading to formation of the double bond between C-5 and C-6, a 3α-tosyloxy-Δ^5 compound is produced as an intermediate. The latter has the substituent at C-3 in the axial configuration and is therefore readily converted to the heteroannular diene. This has been clearly demonstrated in the case of epicholesterol tosylate (3) which on acetolysis affords quantitatively cholestadiene. It is thus obvious that increased yields of 3β-hydroxy-Δ^5 compounds must be due to an increased rate of S_N2 at C-3 or, in other words, due to a relative decreased rate of E1 at C-6. Changing the solvents as indicated above provides a reaction medium that becomes progressively more alkaline; it is well known that unimolecular eliminations proceed more readily in acid solution mainly because ionization or carbonium ion formation is the result of electrophilic attack. The increased yield of 3β-hydroxy-Δ^5 steroid is therefore ascribed to a suppression in the rate of elimination at C-6 in the strongly basic medium of aqueous dimethylformamide containing potassium acetate. Other factors such as dielectric constant of the solvent, temperature, and steric considerations enter undoubtedly into the mechanism of the reaction but it is believed that the pH of the medium is the most important contribution.

EXPERIMENTAL[2]

3α,6α,24-Trihydroxy-24,24-diphenyl-cholane (II)

A Grignard reagent was prepared from magnesium turnings (19.2 gm.) and bromobenzene (85 ml.) in tetrahydrofuran (150 ml.). There was then added a solution of methyl hyodesoxycholate benzene complex (25 gm.) in tetrahydrofuran (175 ml.) and the mixture was refluxed for 15 hr. with constant stirring. The solution was poured into ice-cold, dilute acid and the resulting precipitate was filtered off, washed with water and toluene to yield 26.2 gm. of material,

[2]*The microanalyses were kindly performed by Mr. E. Thommen, Basel, Switzerland.*

m.p. 194–201°C. The toluene extract was evaporated to dryness and the residue crystallized from acetone to provide an additional 3.2 gm. of product, m.p. 133° and 204°C. Recrystallization from benzene gave II, m.p. 204.5–206.5°C.

3α,6α-Diacetoxy-24,24-diphenyl-Δ^{23}-cholene (*IIIb*)

Compound II (8 gm.) was refluxed for five hours with acetic acid (40 ml.) and acetic anhydride (8 ml.). The solution was then poured into water and the precipitate was filtered off, washed, and dried to provide III*b* (8.93 gm.). This material was recrystallized first from aqueous acetone then from methanol to give crystals, m.p. 122–124°C. and $[\alpha]_D^{26}$ +43.6° (*c*, 1.334, dioxane).

3α,6α-Dihydroxy-24,24-diphenyl-Δ^{23}-cholene (*IIIa*)

Hydrolysis of III*b* was carried out by refluxing with 4% methanolic potassium hydroxide for two hours. The solution was poured into water and the precipitate, after being washed and dried, was recrystallized from aqueous methanol to yield nearly quantitatively III*a*, m.p. 184–186°C., $[\alpha]_D^{26}$ +36.8° (*c*, 0.891, dioxane) and $E_{1cm}^{1\%}$ 305 (λ_{max} 250 mμ).

3α,6α-Ditosyloxy-24,24-diphenyl-Δ^{23}-cholene (*IIIc*)

Compound III*a* (5 gm.) was dissolved in pyridine (20 ml.) and tosyl chloride (5.7 gm.) was added. After 48 hr. at 20°C. the excess tosyl chloride was decomposed by addition of water (2 ml.), the solution was then poured into dilute acid and extracted with ether. The solvent extract was washed with dilute acid, then with water, dried over sodium sulphate, and evaporated to a small volume. Crystallization provided 7.4 gm. of III*c*, m.p. 130–132°C. Three crystallizations from ether and iso-octane gave material, m.p. 133–135°C. and $[\alpha]_D^{23}$ +30.6° (*c*, 1.425, dioxane). Analysis: Calcd. for $C_{50}H_{60}O_6S_2$: C, 73.13; H, 7.37; S, 7.81. Found: C, 72.98, 73.00; H, 7.46, 7.52; S, 8.04, 7.99.

3α,6α-Diacetoxy-24,24-diphenyl-$\Delta^{20,23}$-choladiene (*IVb*)

Compound III*b* (5 gm.) was dissolved in hexane (60 ml.) and there was then added sodium bicarbonate (0.9 gm.), N-bromosuccinimide (1.8 gm.), and α,α′-azo-diisobutyronitrile (150 mgm.) or a 25% solution of diacetyl peroxide in dimethyl phthalate (0.2 ml.). This mixture was refluxed for one hour while being stirred vigorously. The precipitated succinimide was then removed by filtration and the filtrate added to acetic acid (55 ml.) containing sodium acetate (5 gm.). After removal of hexane by distillation, the solution was refluxed for one-half hour and finally poured into water to provide, after filtration and drying, 4.96 gm. of crude IV*b*. This material had $E_{1cm}^{1\%}$ 398 (λ_{max} 306 mμ), indicating a yield of 85.6%. Repeated recrystallization from methanol and ethyl acetate afforded pure IV*b*, m.p. 125–126°C., $[\alpha]_D^{24}$ +49.2° (*c*, 2.344, chloroform), $[\alpha]_D^{24}$ +35.1° (*c*, 3.126, dioxane), and $E_{1cm}^{1\%}$ 462 (λ_{max} 306 mμ). This compound gave a green color with trichloroacetic acid, a deep brown with tetranitromethane, and a wine-red in the Liebermann–Burchard reaction. Analysis: Calcd. for $C_{40}H_{50}O_4$: C, 80.77; H, 8.47. Found: C, 80.85, 80.83; H, 8.79, 8.72.

3α,6α-Dihydroxy-24,24-diphenyl-Δ^{20,23}-choladiene (*IVa*)

The diacetate (IV*b*) was saponified by refluxing with 4% methanolic potassium hydroxide. Repeated alternate recrystallization from benzene and aqueous methanol yielded IV*a*, m.p. 211.5–216°C., $[\alpha]_D^{24}$ +48.5° (*c*, 2.579, chloroform) and $E_{1cm}^{1\%}$ 555 (λ_{max} 306 mμ). Analysis: Calcd. for $C_{36}H_{46}O_2$: C, 84.66; H, 9.08. Found: C, 84.71, 84.70; H, 9.08, 9.10.

3α,6α-Ditosyloxy-24,24-diphenyl-Δ^{20,23}-choladiene (*IVc*)

Compound IV*a* (2 gm.) dissolved in pyridine (10 ml.) was treated with tosyl chloride (1.8 gm.). After 48 hr. at 20°C., the excess reagent was decomposed by addition of ice, the mixture was poured into dilute acid and extracted with chloroform. The solvent extract was washed, dried, and evaporated leaving a residue which crystallized from ether to give 2.9 gm. (91%) of IV*c*, m.p. 149–151°C. Two further recrystallizations from ether gave material, m.p. 156–157°C. (decomp.) and $[\alpha]_D^{20}$ +26.2° (*c*, 1.44, dioxane). Analysis: Calcd. for $C_{50}H_{58}O_6S_2$: C, 73.31; H, 7.14; S, 7.83. Found: C, 73.26, 73.20; H, 7.19, 7.23; S, 8.05, 7.99.

3α,6α-Dihydroxy-pregnan-20-one (*VIIIa*)

A solution of IV*b* (17.7 gm.) in chloroform (200 ml.) and 80% acetic acid (220 ml.) was cooled to 0°C. and there was then added within one-half hour 80% acetic acid (200 ml.) containing chromic acid (12.3 gm.). The solution was stirred at 0°C. for four hours, the excess oxidizing agent was destroyed by addition of sodium bisulphite, and the solvents were evaporated *in vacuo*. The residue was diluted with water and extracted with ether, the solvent extract was washed and taken to dryness.

Hydrolysis of the residue with methanol (300 ml.) and concentrated hydrochloric acid (5 ml.) at 20°C. for 14 hr. was followed by neutralization with sodium bicarbonate. The methanol was evaporated and the residue taken up in ether–chloroform and saturated salt solution. The solvent extract was washed once more with salt solution, dried, and evaporated. The residue was dissolved in hot benzene (100 ml.), the solution cooled, the precipitate filtered off and dried to provide 7.82 gm. (78%) of crystals, m.p. 90–95° and 179–181°C. Recrystallization from ethyl acetate afforded VIII*a*, m.p. 192–193°C. and $[\alpha]_D^{24}$ +69.7° (*c*, 1.597, dioxane). Analysis: Calcd. for $C_{21}H_{34}O_3$: C, 75.40; H, 10.25. Found: C, 75.26, 75.23; H, 10.30, 10.37.

3α,6α-Ditosyloxy-pregnan-20-one (*VIIIc*)

Compound VIII*a* (2.5 gm.) was treated in the usual manner with pyridine (10 ml.) and tosyl chloride (4.2 gm.). The reaction mixture, after addition of dilute acid, was extracted with ether and the solvent extract worked up to give a residue which crystallized from ether to afford VIII*c* (3.93 gm.; 82%), m.p. 140–142°C. Two further recrystallizations from ether gave material, m.p. 147–148°C. and $[\alpha]_D^{24}$ +34° (*c*, 1.342, dioxane). Analysis: Calcd. for $C_{35}H_{46}O_7S_2$: C, 65.39; H, 7.21; S, 9.98. Found: C, 65.45, 65.43; H, 7.37, 7.32; S, 9.69, 9.75.

3α,6α-Dihydroxy-pregnan-20-one Ethylene Ketal (*IXa*)

The ketone VIII*a* (3.06 gm.) was dissolved in dry benzene (100 ml.) and ethylene glycol (6 ml.). After addition of *p*-toluenesulphonic acid monohydrate (150 mgm.), the mixture was stirred and refluxed for four hours, during which time water was continually removed by the use of a Dean-Stark trap. On cooling, saturated sodium bicarbonate solution (2 ml.) was added and the solvents were evaporated *in vacuo*. The solid residue was shaken with saturated salt solution, filtered off, washed with water, and dried to furnish 3.34 gm. (98%) of material, m.p. 218–228°C. Recrystallization from methanol afforded pure IX*a*, m.p. 227–228°C. and $[\alpha]_D^{26}$ +6.44° (*c*, 1.63, pyridine). Analysis: Calcd. for $C_{23}H_{38}O_4$: C, 72.97; H, 10.11. Found: C, 72.81, 72.86; H, 10.07, 10.03.

Acetylation of IX*a* provided the corresponding diacetate (IX*b*), crystallized from aqueous methanol, m.p. 125–132°C. Two recrystallizations from the same solvent yielded material, m.p. 139–140°C. and $[\alpha]_D^{24}$ +15.03° (*c*, 1.55, pyridine). Analysis: Calcd. for $C_{27}H_{42}O_6$: C, 70.10; H, 9.15. Found: C, 69.84, 70.04; H, 9.32, 9.40.

3α,6α-Ditosyloxy-pregnan-20-one Ethylene Ketal (*IXc*)

Tosylation of IX*a* (0.9 gm.) with pyridine (6 ml.) and tosyl chloride (1.4 gm.) was carried out as described above. The products were taken up in ethylene dichloride and the solvent extract was washed, dried, and evaporated. From ether, crystals of IX*c* (1.42 gm.; 87%), m.p. 147–148°C., were deposited. Crystallization from benzene–hexane raised the m.p. to 151.5–152°C. and this sample then had $[\alpha]_D^{24}$ +5.21° (*c*, 1.515, pyridine). Analysis: Calcd. for $C_{37}H_{50}O_8S_2$: C, 64.72; H, 7.28; S, 9.32. Found: C, 64.60, 64.59; H, 7.58, 7.35; S, 9.16.

Pregnenolone Ethylene Ketal (*X*)

Compound IX*c* (8 gm.) was dissolved in dimethylformamide (85 ml.) and treated with a solution of potassium acetate (12 gm.) in water (20 ml.). The solution was kept at 95°C. for four hours. After complete removal of the solvents *in vacuo*, the residue was saponified by refluxing with methanolic potassium hydroxide. Part of the methanol was evaporated, the residue was diluted with water, cooled, and the resulting precipitate was filtered off. Thorough washing and drying gave a residue (4.38 gm.), m.p. 107–125°C. This was recrystallized repeatedly from methanol containing a few drops of pyridine to yield a pure sample of X, m.p. 164–167°C. and $[\alpha]_D^{24}$ −30.6° (*c*, 1.86, pyridine). Analysis: Calcd. for $C_{23}H_{35}O_3$: C, 76.62; H, 10.07. Found: C, 76.62, 76.54; H, 10.16, 10.17.

Progesterone 20-Ethylene Ketal (*XI*)

A solution of X (3.5 gm.) in toluene (100 ml.) and cyclohexanone (30 ml.) was distilled briefly to remove traces of moisture and, after addition of aluminum isopropoxide (2 gm.), the solution was refluxed for one hour. The mixture was treated with water (20 ml.), the solvents were removed *in vacuo*, and the residue was taken up in benzene. The solvent extract was filtered and

evaporated to give a solid which was leached with hexane and filtered off to yield 3.25 gm. (93%) of crude XI, m.p. 184–189°C. Recrystallization from ethyl acetate provided material, m.p. 189–191°C., $[\alpha]_D^{24}$ +97.5° (*c*, 1.13, pyridine), and $E_{1cm}^{1\%}$ 447 (λ_{max} 242 mμ). Analysis: Calcd. for $C_{23}H_{34}O_3$: C, 77.05; H, 9.56. Found: C, 77.04, 77.11; H, 9.61, 9.59.

Progesterone (XII)

Compound XI (2 gm.) was dissolved in acetone (30 ml.) and water (3 ml.) by warming briefly and, after addition of *p*-toluenesulphonic acid (100 mgm.), the solution was kept at 20°C. for 15 hr. The acetone was then evaporated, the residue was treated with a dilute solution of sodium bicarbonate, and the precipitate was filtered off, washed with water, and dried. This product (1.82 gm.), m.p. 117–128°C., was crystallized from aqueous acetone to provide progesterone, m.p. 131–133°C., $[\alpha]_D^{24}$ +177.2° (*c*, 2.5, dioxane).

Methyl Hyodesoxycholate Ditosylate (Ic)

Methyl hyodesoxycholate (25 gm.) was dissolved in dry pyridine (50 ml.) and tosyl chloride (28.8 gm.) was added. The solution was kept at room temperature for two days. Subsequently, the mixture was cooled, the excess reagent was decomposed by ice, and the solution was poured into ice-cold, dilute hydrochloric acid. After the mixture was stirred for one-half hour, the precipitate was filtered, washed with water, and dried to yield 43.9 gm. of material. Recrystallization from ethyl acetate afforded 41.6 gm. (95%) of Ic, m.p. 165–167°C. and $[\alpha]_D^{24}$ +9.8° (*c*, 1.016, dioxane). Analysis: Calcd. for $C_{39}H_{54}O_8S_2$: C, 65.53; H, 7.61; S, 8.97; OCH_3, 4.34. Found: C, 65.60, 65.55; H, 7.68, 7.65; S, 9.19; OCH_3, 4.50.

3β-Hydroxy-Δ⁵-cholenic Acid (V)

A solution of potassium acetate (7.3 gm.) in water (3.5 ml.) and dimethylformamide (40 ml.) was heated to 100–105°C. After addition of Ic (5 gm.), the solution was kept at the above temperature for five hours. It was then poured into cold, dilute hydrochloric acid and the resulting precipitate was filtered off and washed with water. The wet solid was saponified by refluxing with 4% methanolic potassium hydroxide (70 ml.) for two hours. The solution was poured into dilute acid, the precipitate was filtered, washed, and dried. Recrystallization from ethyl acetate yielded 1.92 gm. (73%) of product, m.p. 220–227°C. Two crystallizations from acetic acid gave pure V, m.p. 230–233°C., giving an insoluble digitonide and a yellow coloration with tetranitromethane. The identity of V was conclusively established by melting point and mixed melting point of the corresponding methyl ester and methyl ester acetate.

The filtrate was evaporated to dryness to leave a residue (0.71 gm.) which was found, by ultraviolet absorption measurement at 235 mμ, to contain 0.3 gm. of choladienic acid.

3β-Hydroxy-24,24-diphenyl-Δ⁵,²³-choladiene (VI)

The dehydrotosylation of IIIc (5 gm.) was carried out under the conditions described in the preceding experiment. After saponification and crystallization of the residue from acetone, there was obtained 1.95 gm. of crystals, m.p.

164–170°C. Recrystallization from the same solvent gave a pure sample of VI, m.p. 176–179°C.

3β-Hydroxy-24,24-diphenyl-$\Delta^{5,20,23}$-cholatriene (*VII*)

Compound IV*c* (81.5 gm.) was dehydrotosylated in the manner set forth for the preparation of V. Following saponification, the reaction products were crystallized from ethanol to give 38.5 gm. (78%) of VII, m.p. 130–137°C. Recrystallization from hexane, then from ethanol, gave m.p. 157–161°C.

A sample of VII (1 gm.) dissolved in ethyl acetate (15 ml.) was added to a warm solution of anhydrous oxalic acid (0.2 gm.) in ethyl acetate (2 ml.). A precipitate formed at once; after refrigeration, the crystals were filtered off, washed with ethyl acetate, and dried to yield 0.95 gm. of the adduct. Three recrystallizations from ethyl acetate provided a pure sample of the adduct, m.p. 192–195°C. and $[\alpha]_D^{20}$ −14.2° (*c*, 1.01, dioxane). Analysis: Calcd. for $C_{36}H_{44}O.\frac{1}{2}C_2H_2O_4$: C, 82.64; H, 8.44. Found: C, 82.53, 82.63; H, 8.56, 8.63.

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STUDIES IN THE WAGNER–MEERWEIN REARRANGEMENT. PART I[1]

By F. A. L. Anet and P. M. G. Bavin[2]

ABSTRACT

The preparation by a convenient route of 9-methyl, ethyl, isopropyl, *t*-butyl, and benzyl phenanthrenes is described. This consists of the alkylation of methyl fluorene-9-carboxylate under mild conditions, reduction of the ester group with lithium aluminum hydride, and then tosylation of the carbinol. The tosyl esters so prepared rearrange to alkylphenanthrenes with simultaneous loss of the elements of toluenesulphonic acid, when heated alone or in formic acid. Dehydration of the carbinols at 160° with polyphosphoric acid also promotes rearrangement.

Application of the Wagner–Meerwein rearrangement to the synthesis of polycyclic hydrocarbons and their derivatives has received little attention. The first recognized example reported (2) was the dehydration and rearrangement of 9-phenyl-9-(α-hydroxybenzyl)-fluorene to 9,10-diphenylphenanthrene under the influence of iodine in acetic acid. The same product had been obtained earlier by the reduction of 9-phenyl-9-benzoylfluorene with red phosphorus and iodine (34).

More recently, phenanthrene has been obtained from 9-fluorenylmethanol (7), and this has been extended to the preparation of phenanthrene-(9,10-$^{14}C_1$) (13), 1,2-benzanthracene-(5,6-$^{14}C_1$) (14), and chrysene-(5,6-$^{14}C_1$) (15). 2,7-Dibromophenanthrene has also been prepared from the appropriate fluorene derivative (9). In all of these examples, phosphorus pentoxide in boiling xylene was used to effect rearrangement.

Polyphosphoric acid at 160° has been used to bring about the rearrangement of 9-fluorenylmethyl acetate and its 2-nitro derivative to give phenanthrene and 2-nitrophenanthrene, respectively, in good yield (3).

Two types of fluorene derivatives capable of undergoing the Wagner–Meerwein rearrangement are distinguished, differentiated by the 9-carbon atom being respectively tertiary and quaternary, I and II. Compounds of type I may give derivatives of both phenanthrene and dibenzfulvene, whilst those of type II may give only the former. Migration of the group R in compounds of type II has not been observed. Conditions under which the different products are obtained have been studied (17), and it was found that the best yields of phenanthrene derivatives were obtained by using phosphorus pentoxide in boiling xylene.

As a preliminary to the study of more complex systems, we have made a detailed examination of a convenient route to the 9-alkylphenanthrenes. This is based on methyl fluorene-9-carboxylate, the parent acid of which is simply prepared from benzilic acid (29), in contrast to a recent statement in the

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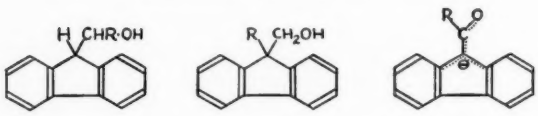

I II III

literature (33). The acidity of the 9-hydrogen of this ester has been known for some time (33, 35, 38, 39; see also 16, 17, 28), and 9-alkyl derivatives of the (ethyl) ester were prepared by Wislicenus (38, 39). The ester has also been utilized in the Michael reaction (11, 31, 33, 36). 9-Formylfluorene and related compounds have been alkylated (8).

Methyl fluorene-9-carboxylate and its amide are soluble in aqueous alcohol containing strong alkali to give yellow solutions which show a pale blue fluorescence. These solutions are thought to contain the anion III, where R is $-OCH_3$ or $-NH_2$. The existence of the anion is well illustrated in Fig. 1, which

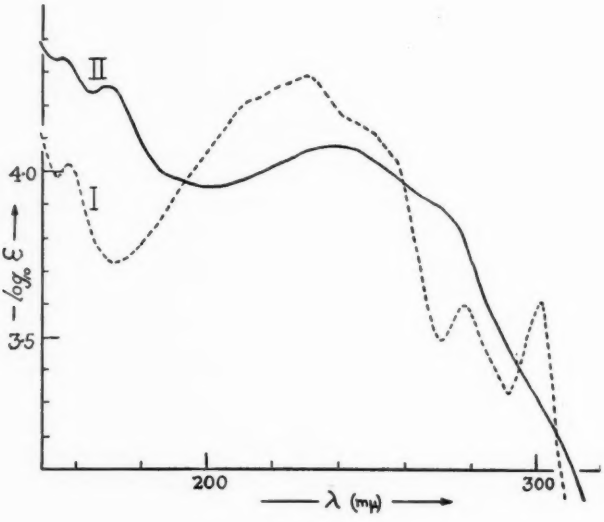

FIG. 1.

shows the ultraviolet spectra of methyl fluorene-9-carboxylate in methanol (I) and in methanolic sodium methoxide (II). It is concluded that conversion to the anion was almost complete under the conditions employed, a view which is supported by the failure of the ester to undergo base-catalyzed transesterification under conditions where the 9-methyl derivative showed this reaction (see below).

Alkylation of methyl fluorene-9-carboxylate proceeded smoothly in dry methanol in the presence of excess sodium methoxide and alkyl halide. In this

way we prepared the 9-methyl, ethyl, propyl, isopropyl, allyl, butyl, *s*-butyl, *t*-butyl, octyl, cyclohexyl, and benzyl derivatives, all but the octyl being obtained crystalline. This procedure is very much more convenient than that employed by Wislicenus (38, 39), who used the ethyl ester and excess potassium as base. The latter ester gives rise to low-melting derivatives, making their isolation and purification in good yield difficult. We obtained methyl 9-*t*-butylfluorene-9-carboxylate in 94% yield, in striking contrast to the *t*-butylation of malonic ester and related compounds which gives negligible yields.

Methyl 9-methylfluorene-9-carboxylate underwent base-catalyzed transesterification under conditions as mild as those used for the alkylations, but the highly hindered 9-*t*-butyl derivative did not do so to a demonstrable extent.

Reduction of the 9-alkyl esters by lithium aluminum hydride proceeded smoothly, although an extended reaction time was necessary in the case of the *t*-butyl derivative to ensure complete reaction. The 9-alkyl-9-fluorenylmethanols so prepared were readily tosylated, giving easily crystallized esters.

Conversion to the 9-alkylphenanthrenes was effected in three ways: *A*, the carbinol was heated with polyphosphoric acid at 160°; *B*, the tosyl ester was boiled under reflux for a few minutes with formic acid; *C*, the tosyl ester was heated to its melting point. *B* was the most convenient method. We prepared the known 9-methyl, ethyl, isopropyl, and benzyl phenanthrenes, as well as the previously unknown and difficultly accessible 9-*t*-butylphenanthrene. It is concluded that the method is of wide applicability.

9-*t*-Butyl-9-fluorenylmethanol gave some unexpected results. Treatment by method *A* gave a mixture of phenanthrene and 9-*t*-butylphenanthrene, together with a trace of a third compound, the presence of which prevented an analysis of the mixture being made from its ultraviolet spectrum. By starting with pure methyl fluorene-9-carboxylate and carefully purifying the derivatives, we satisfied ourselves that the phenanthrene did not arise from 9-fluorenylmethanol present as an impurity. Additional experiments showed that 9-*t*-butylphenanthrene was stable in polyphosphoric acid at 200°, and that phenanthrene was not alkylated by *t*-butyl alcohol under similar conditions.

There can be little doubt that the rearrangement of 9-fluorenylmethanol and its derivatives takes place through an intermediate carbonium ion, in a manner analogous to more classical examples[3] (19, page 474 ff.; see also 17). The formation of phenanthrene from 9-*t*-butyl-9-fluorenylmethanol may be formulated as shown (Fig. 2), this mechanism accounting for the formation of phenanthrene on the basis of the stability of the *t*-butyl carbonium ion.

Wittig (40) found that treatment of 9-benzyl-9-fluorenylmethanol at 100° with phosphorus tribromide gave an excellent yield of 9-benzylphenanthrene. We have found that 9-*t*-butyl-9-fluorenylmethanol when treated with phosphorus trichloride under similar conditions does not give 9-*t*-butylphenanthrene. Instead a crystalline derivative of m.p. 145° was obtained. This had a typical fluorene spectrum (12, 20) and was soluble in aqueous potassium hydroxide; it reprecipitated on acidification. When boiled with formic acid

[3]*Wittig and co-workers recently obtained 9-benzylphenanthrene in good yield when 9-benzyl-9-fluorenylmethyl bromide was treated with ethereal lithium phenyl (40). This reaction cannot be formulated as a simple Wagner–Meerwein rearrangement.*

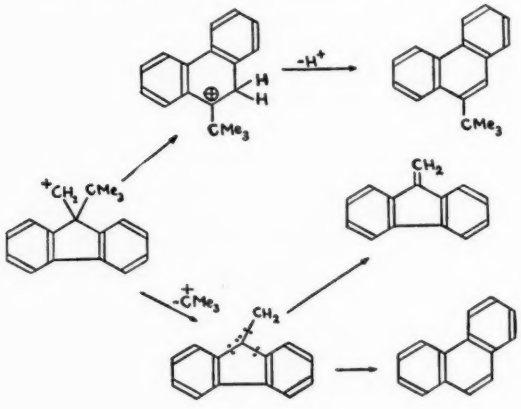

FIG. 2.

for a few minutes, it gave 9-*t*-butylphenanthrene. These properties and elementary analyses show it to be the phosphite, RO.P(OH):O. Its isolation and rearrangement suggest that similar esters are intermediates in those rearrangements brought about by phosphorus pentoxide or polyphosphoric acid, such esters, like the tosylates, tending to undergo solvolysis by an S_N1 process. Heating 9-*t*-butyl-9-fluorenylmethanol with formic acid gave only the formate, although under similar conditions trichloracetic acid gave some 9-*t*-butylphenanthrene.

Mild hydrolysis of the methyl 9-alkylfluorene-9-carboxylates affords the acids, more vigorous conditions giving the 9-alkylfluorenes (31). Preparation of the 9-*t*-butyl acid proved difficult, owing to the highly hindered system. Its melting point (237°) was considerably higher than that reported earlier (16, 224–226°), and it exists in at least two crystalline forms. Dimorphism was also observed with 9-allylfluorene-9-carboxylic acid. The previously unknown 9-*t*-butylfluorene has now been prepared.

In a recent communication (24), the phenylation of diethyl ketone was described, using sodamide and bromobenzene in liquid ammonia. Attempts to prepare methyl 9-phenylfluorene-9-carboxylate by a similar procedure have failed, a small quantity of what is probably 9,9′-difluorenyl being isolated.

Attempts to prepare 9-phenylphenanthrene from the readily accessible 9-(α-hydroxybenzyl)-fluorene failed. The latter compound was obtained in good yield from 9-benzoylfluorene by reduction with potassium borohydride. The reduction did not proceed in the presence of an excess of strong alkali, owing to the formation of the anion (III, R is phenyl) as shown by the deep yellow color of the solution. Treatment of the carbinol with polyphosphoric acid did not give 9-phenylphenanthrene, giving instead 9-benzalfluorene. The ultraviolet spectrum was in agreement with this structure for the product (25).

Recently, Martin and co-workers (26) have reported the results of solvolytic studies on 9-fluorenylmethyl esters. The trichloracetate, for example, was found

to undergo solvolysis in neutral aqueous solution by a unimolecular mechanism involving alkyl–oxygen fission. The product isolated was 9-fluorenylmethanol, from which it was concluded that the 9-fluorenylmethyl cation reacted much faster with the solvent than it rearranged, in contrast to the 9-alkyl-9-fluorenylmethyl cations reported in this paper. The work of Martin suggested that the solvolysis of 9-fluorenylmethyl tosylate would not give phenanthrene, the parent alcohol being the expected product.

We have made repeated attempts to prepare 9-fluorenylmethyl tosylate, but the elementary analyses have been consistently low for carbon. The ultraviolet spectrum of the products obtained by boiling the tosylate with formic acid or neutral aqueous dioxane showed the presence of a considerable proportion of phenanthrene. Additional experiments showed that the phenanthrene did not arise from 9-fluorenylmethanol.

The tosylate of 9-hydroxymethylenefluorene has been prepared, but could not be made to undergo rearrangement.

Attempts have been made to prepare fluorene-9-carboxylic acid from benzilic acid without the use of aluminum chloride. Treatment with polyphosphoric acid at 180° gave a small yield of the desired product. Attempted tosylation of benzilic acid gave benzilide in excellent yield, probably through the mixed anhydride of benzilic and toluenesulphonic acids. This view is supported by the failure of methyl benzilate to react. Treatment of benzilic acid or its methyl ester with anhydrous hydrogen fluoride gave none of the desired products.

This work is being actively continued. The ultraviolet spectra of the 9-alkylphenanthrenes will be reported shortly.

EXPERIMENTAL

All melting points are uncorrected. Values below 200° were recorded in capillaries (oil bath); those above 200° were obtained using a hot-stage microscope. Ultraviolet spectra were measured in ethanol with a Beckmann DK.2 self-recording spectrophotometer. Microanalyses are by Geller Laboratories, New Jersey, U.S.A.

Methyl Fluorene-9-carboxylate

Fluorene-9-carboxylic acid was prepared from benzilic acid (29), the scale being increased fourfold.

The dried acid (1 part) and dry methanol (15 vol.) were boiled under reflux for two hours with a catalytic amount of concentrated sulphuric acid. The volume was then reduced by a half by slow distillation, made up by the addition of fresh methanol, and the mixture again boiled for two hours. After cooling, the acid was neutralized by the cautious addition of solid sodium bicarbonate and the solution filtered. Evaporation of the filtrate gave an oil which was dissolved in the minimum of benzene–hexane (1:2) and passed through a column of activated alumina. Further elution with hexane and evaporation of the combined eluants, followed by crystallization from methanol, gave large pale yellow prisms, m.p. 64–65° (reported m.p. 66.5° (5); 63–66° (33)), raised to 65° by a further crystallization. The yield of once-crystallized material was 71–84% based on benzilic acid.

The ester was readily soluble in aqueous alcohol containing sodium hydroxide to give a yellow solution having a pale blue fluorescence. Acidification of a freshly prepared solution gave the ester unchanged.

The ester (1 gm.) was dissolved in anhydrous ethanol (50 ml.) containing sodium ethoxide from 1 gm. of sodium. After it had been left at room temperature for 24 hr., the solution was acidified and the product isolated with chloroform. Crystallization from methanol gave the ester unchanged (0.8 gm.), m.p. and mixed m.p. 64–65°.

The amide was prepared by boiling the ester (0.5 gm.) in ethylene glycol (30 ml.) with ammonia (4 ml., d. 0.88) for two hours. Small quantities of ammonia were added from time to time. On cooling, long colorless silky needles (0.2 gm.) separated. After recrystallization from ethanol (Norit) these had m.p. 253°. (Reported m.p. 251° (30).) A solution in ethanolic sodium hydroxide was yellow.

The ester formed a *1,3,5-trinitrobenzene complex*, yellow needles from methanol, m.p., 97–97.5°. Calc. for $C_{21}H_{15}O_8N_3$: C, 57.73; H, 3.44; N, 9.52. Found: C, 57.67; H, 3.46; N, 9.61%.

Preparation of the Methyl 9-Alkylfluorene-9-carboxylates

Methyl 9-Methylfluorene-9-carboxylate

Methyl fluorene-9-carboxylate (4.5 gm.) was dissolved in methanolic sodium methoxide, prepared from sodium (1.9 gm., 4.5 at. equiv.) and dry methanol (50 ml.). Methyl iodide (10 ml.) was added and the solution left overnight at room temperature. Access to moisture was prevented by a calcium chloride guard tube. Next morning, the solution was poured into cold dilute hydrochloric acid and the product isolated with chloroform. Crystallization from chloroform–hexane gave slightly yellow prisms, m.p. 108–109°, (4.2 gm., 92%). Further crystallizations gave colorless prisms of the same m.p. (Recorded m.p. 108–109° (31).)

Hydrolysis of the ester (1 gm.) for a few minutes at 50° in aqueous ethanol containing potassium hydroxide (2 gm.) gave 9-methylfluorene-9-carboxylic acid (0.6 gm.). Recrystallization from methanol gave long needles, m.p. 170–171°. (Recorded m.p. 168° (35); 168–169° (31); 170–171° (18).)

Ethyl 9-Methylfluorene-9-carboxylate

(*a*) The alkylation was carried out as described above except that ethanol replaced the methanol. The product was an oil which slowly crystallized when kept with hexane in the ice chest. Recrystallization from hexane and collection in a precooled funnel gave needles, m.p. 31°, (2.7 gm.). (Reported m.p. 33° (38).)

(*b*) Methyl 9-methylfluorene-9-carboxylate (1 gm.) was dissolved in ethanolic sodium ethoxide (from 1 gm. of sodium). After 24 hr., the product was isolated in the usual way and crystallized from hexane to give needles (0.8 gm.), m.p. 30–31°, undepressed when mixed with the sample prepared by method (*a*).

Hydrolysis of the samples prepared by both methods gave 9-methylfluorene-9-carboxylic acid, m.p. and mixed m.p. 169–170°.

Methyl 9-Ethylfluorene-9-carboxylate

This compound was prepared as described for the methyl analogue from the ester (4.5 gm.), sodium (1 gm., 2.3 equiv.), and ethyl iodide (12 ml.). Crystallization from hexane gave long colorless prisms (4.4 gm., 86%), m.p. 79–81°. An analytical specimen was obtained after three further crystallizations, m.p. 81.5–82.0°. Calc. for $C_{17}H_{16}O_2$: C, 80.92; H, 6.39. Found: C, 81.0; H, 6.42%.

Methyl 9-Allylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (5 gm.), sodium (1.5 gm., 3 equiv.), and allyl bromide (12 ml.). Allyl chloride proved less satisfactory. Crystallization from methanol gave soft blades (5 gm., 85%), m.p. 72–74°, raised to 75° by a further crystallization. Calc. for $C_{18}H_{16}O_2$: C, 81.79; H, 6.10. Found: C, 81.75; H, 6.31%.

Hydrolysis as for the methyl analogue and crystallization from hexane gave 9-allylfluorene-9-carboxylic acid as prisms, m.p. 132–132.5°. On the hot stage the acid melted at 120°, recrystallized at 126°, and finally melted at 134–136°. This sequence was observed once in the capillary m.p. apparatus. (Reported m.p. 131.5–132.5° (1).)

Methyl 9-Propylfluorene-9-carboxylate

(*a*) This was prepared as described for the methyl analogue from the ester (1.1 gm.), sodium (0.4 gm., 3 equiv.), and propyl bromide (7 ml.). Two crystallizations from methanol gave long white needles (0.87 gm., 67%), m.p. 85–85.5°. Calc. for $C_{18}H_{18}O_2$: C, 81.17; H, 6.81. Found: C, 81.5; H, 6.96%.

(*b*) The 9-allyl ester (0.39 gm.) was hydrogenated in ethanol over 10% palladium-on-charcoal. Hydrogen (39.7 ml. at 21° and 733 mm. partial pressure, 1.07 moles) was absorbed in five minutes. Crystallization of the product from hexane gave needles (0.365 gm., 92%), m.p. 85°, not depressed when mixed with the sample prepared by method (*a*).

Methyl 9-Isopropylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (5 gm.), sodium (1.5 gm., 3 equiv.), and isopropyl bromide (10 ml.). The product crystallized as prisms from methanol (4.8 gm., 81%), m.p. 78–79°, raised to 79–80° by successive crystallizations from methanol and acetone. Calc. for $C_{18}H_{18}O_2$: C, 81.17; H, 6.81. Found: C, 81.33; H, 6.75%.

Methyl 9-Butylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (1.5 gm.), sodium (0.2 gm., 1.3 equiv.), and butyl iodide (4 ml.). The product slowly crystallized when kept in the ice chest for a few days. Recrystallization was difficult but two crystallizations from ice-cold methanol with seeding gave long colorless needles, m.p. 34–34.5°. Calc. for $C_{19}H_{20}O_2$: C, 81.39; H, 7.19. Found: C, 81.45; H, 7.30%.

Methyl 9-s-Butylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (1.5 gm.), sodium (0.5 gm., 3.3 equiv.), and *s*-butyl bromide (8 ml.). Crystal-

lization from methanol (Norit) and subsequent crystallizations from methanol and acetone gave colorless prisms and rectangular tablets (1.1 gm., 59%), m.p. 70–71°. Under the microscope, the crystals showed extensive twinning. Calc. for $C_{19}H_{20}O_2$: C, 81.39; H, 7.19. Found: C, 81.6; H, 7.3%.

Methyl 9-t-Butylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (15 gm., m.p. 65°), sodium (6 gm., 4 equiv.), and freshly prepared *t*-butyl bromide (40 ml.). Tertiary butyl chloride proved less satisfactory. When the alkyl halide was added, the solution turned bright orange-red, the color fading overnight. Crystallization from methanol–acetone (10:1) afforded thick prismatic needles (13.3 gm., 71%), m.p. 113°, not raised by further crystallizations. Concentration of the mother liquors gave a second crop, m.p. 110–112°, (2.1 gm., bringing the yield up to 94%).

The infrared spectrum was measured in carbon tetrachloride solution and showed sharp bands at 1368 and 1401 cm.$^{-1}$ with the former the more intense. (Bellamy (4, p. 23) records 1365 and 1395 cm.$^{-1}$ for the *t*-butyl group, the bands having the same intensity distribution.) Calc. for $C_{19}H_{20}O_2$: C, 81.39; H, 7.19. Found: C, 81.33; H, 7.24%.

The ester was recovered unchanged after treatment with ethanolic sodium ethoxide under the conditions used for the methyl analogue. Hydrolysis was slow, 9-*t*-butylfluorene-9-carboxylic acid being prepared as follows: the ester (1 gm.) was dissolved in ethanol (50 ml.) and a solution of potassium hydroxide (5 gm.) in water (40 ml.) added. The solution was maintained at 80–85° for three hours, small quantities of ethanol being added at intervals to maintain homogeneity. After the solution had been cooled, ethanol was removed by evaporation and the solution extracted with hexane. The aqueous layer was acidified, giving 9-*t*-butylfluorene-9-carboxylic acid (0.6 gm.). Crystallization from methanol gave prisms and rhombs, which partially melted at 233–235°, recrystallized as irregular prisms, and finally melted at 237°. (Reported m.p. 224–226° (16).[4])

9-t-Butylfluorene

Methyl 9-*t*-butylfluorene-9-carboxylate (0.305 gm.) was boiled under reflux with ethylene glycol (30 ml.) and a solution of potassium hydroxide (2 gm.) in water (2 ml.). The solution rapidly turned yellow, becoming colorless after two hours, during which time a white solid collected in the condenser. The solid was crystallized from methanol, giving white needles (0.105 gm.), m.p. 101°, raised to 101.5° by a further crystallization. The mixed m.p. with fluorene (m.p. 115°) was 75–80°. Calc. for $C_{17}H_{18}$: C, 91.84; H, 8.16. Found: C, 91.99; H, 8.16%.

Methyl 9-Octylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (1.5 gm.), sodium (0.17 gm.), and octyl bromide (6 ml.). The product was

[4]*The discrepancy in the melting point may be due to polymorphism, or possibly due to the fact that the microscope slides are soft glass whilst capillaries are usually Pyrex, surface alkali then being responsible for the variation.*

distilled in a Späth bulb at 1–2 mm., giving a pale yellow oil, b.p. 175–190°, (4.2 gm.), and an almost colorless oil, b.p. 190–200°, (1.5 gm.). Calc. for $C_{23}H_{28}O_2$: C, 82.10; H, 8.39. Found: C, 81.72; H, 8.37%.

Methyl 9-Cyclohexylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (1.5 gm.), sodium (0.5 gm., 3 equiv.), and cyclohexyl bromide (8 ml.). Crystallization from methanol (Norit) and two further crystallizations from acetone gave small glistening prisms, m.p. 121°, (1.6 gm., 76%). Calc. for $C_{21}H_{22}O_2$: C, 82.32; H, 7.24. Found: C, 82.31; H, 7.32%.

Methyl 9-Benzylfluorene-9-carboxylate

This was prepared as described for the methyl analogue from the ester (5 gm.), sodium (1.5 gm., 3 equiv.), and benzyl chloride (12 ml.). Crystallization from methanol–acetone (1:4) gave large pale yellow prisms and rhombs (5.55 gm., 79%), m.p. 71–73°. Two further crystallizations from acetone (Norit) gave colorless prisms, m.p. 74–75°. Calc. for $C_{22}H_{18}O_2$: C, 84.05; H, 5.77. Found: C, 84.46; H, 6.04%.

Preparation of the 9-Alkylphenanthrenes

9-Methylphenanthrene

9-Methyl-9-fluorenylmethanol

This was prepared from the appropriate ester (2.5 gm.) by reduction with lithium aluminum hydride (1.5 moles). The product was crystallized from hexane, giving prismatic needles (2.1 gm., 95%), m.p. 147°. (Reported m.p. 148–149° (17).)

9-Methyl-9-fluorenylmethyl Tosylate

The preceding carbinol (4 gm.) was dissolved in dry pyridine (30 ml.) containing *p*-toluenesulphonyl chloride (1.1 moles). After it had been left for 18 hr. at room temperature, the solution was poured into excess cold dilute hydrochloric acid and the product isolated with chloroform. Crystallization from benzene-heptane (1:5) gave colorless needles (4.2 gm.), m.p. 103–104°. Calc. for $C_{22}H_{20}O_3S$: C, 72.50; H, 5.53. Found: C, 72.59; H, 5.68%.

9-Methylphenanthrene

Method A.—The carbinol (2 gm.) and polyphosphoric acid (120 ml.) were stirred together at 160° for 30 min. After it had been cooled, the solution was poured onto ice and the product isolated with chloroform. Evaporation left a yellow oil which was chromatographed from hexane on alumina. The early fractions gave a white solid, m.p. 91–92°. Crystallization from methanol gave white needles, m.p. 92–92.5°, (1.1 gm., 60%). (Reported m.p. 90–91° (36); 92–93° (17).) The *picrate* crystallized from methanol as orange needles, m.p. 154–155°. (Reported m.p. 152–153° (36).)

Method B.—The tosyl ester (2 gm.) was boiled under reflux for a few minutes with formic acid (30 ml., 88%) and then poured into water. The product was isolated with chloroform and crystallized from methanol to give slightly yellow

plates and prisms (1.1 gm., 80%), m.p. 91–92°, not depressed when mixed with a sample prepared by method *A*.

Method C.—The tosyl ester (0.1 gm.) was heated to its melting point and the products dissolved in ethanol (5 ml.). The ultraviolet spectrum of this solution showed that 9-methylphenanthrene had been formed in practically quantitative yield.

9-Ethylphenanthrene

9-Ethyl-9-fluorenylmethanol

This was prepared in the usual way. It crystallized from hexane as prisms (92%), m.p. 74–76°, raised to 76.5–77.0° by three further crystallizations. Calc. for $C_{16}H_{16}O$: C, 85.67; H, 7.19. Found: C, 85.85; H, 7.29%. The *tosylate* crystallized as needles from heptane (85%), m.p. 134°. Calc. for $C_{23}H_{22}O_3S$: S, 8.47. Found: S, 8.56, 8.59%.

9-Ethylphenanthrene

Method *A* gave a white solid (66%) which crystallized from methanol as small needles, m.p. 62–63°. (Recorded m.p. 62.5–63.0° (6).) The *picrate* separated as orange needles from methanol, m.p. 118–119°. (Reported m.p. 123–124° (6).) Method *B* gave pure 9-ethylphenanthrene in 87% yield, and its formation by method *C* was shown spectroscopically.

9-Isopropylphenanthrene

9-Isopropyl-9-fluorenylmethanol

This was obtained as a colorless oil which failed to crystallize. The *tosyl ester* rapidly crystallized when scratched with hexane. One crystallization from heptane gave long white needles (72% based on the carboxylic ester), m.p. 90–91°. Calc. for $C_{24}H_{24}O_3S$: C, 73.44; H, 6.16. Found: C, 73.61; H, 5.97%.

9-Isopropylphenanthrene

This was prepared by method *B* as a yellow oil. Chromatography followed by crystallization from methanol gave large hexagonal plates (52%), m.p. 41–42°. (Reported m.p. 41–42° (6).) The *picrate* separated as orange needles from methanol, m.p. 106–107°. (Reported m.p. 109–110° (6).)

9-t-Butylphenanthrene

9-t-Butyl-9-fluorenylmethanol

9-*t*-Butyl-9-fluorenylmethanol was prepared in the usual way, except that the reaction time was extended to 24 hr. Crystallization from hexane gave prismatic needles (98%), m.p. 76–77°, not raised by further crystallizations. Calc. for $C_{18}H_{20}O$: C, 85.67; H, 7.99. Found: C, 85.86, 86.04; H, 8.12, 8.23%.

The *formate* was prepared by boiling the carbinol with formic acid for four hours. Recrystallization from methanol gave white needles, m.p. 90°. Calc. for $C_{19}H_{20}O_2$: C, 81.39; H, 7.19. Found: C, 81.1; H, 7.23%. The ultraviolet spectrum of the formic acid mother liquors remaining when the reaction time was extended to 14 hr. showed phenanthrene derivatives not to be present.

The *acetate*, prepared by esterification with acetic anhydride – sulphuric acid, crystallized from hexane as prisms, m.p. 70–71°. Calc. for $C_{20}H_{22}O_2$: C, 81.6; H, 7.53. Found: C, 81.8; H, 7.61%.

The *tosylate* crystallized from hexane as prisms (94%), m.p. 108–110°, raised to 111° by a further crystallization. Calc. for $C_{25}H_{26}O_3S$: S, 7.89. Found: S, 7.72%.

9-t-Butyl-9-fluorenylmethyl Phosphite

The carbinol (1 gm.) and phosphorus trichloride (3 ml., from a new bottle) were heated on the steam bath in a closed vessel for two hours. After it had been cooled, the sirup was stirred with ice water and the product isolated with chloroform. It readily crystallized from methanol as large colorless prisms, m.p. 145°. Calc. for $C_{18}H_{21}O_3P$: C, 68.13; H, 6.69; P, 9.79. Found: C, 69.49; H, 6.98; P, 9.69%.

The phosphite showed a typical fluorene spectrum in the ultraviolet, and was soluble in aqueous potassium hydroxide solution; it reprecipitated upon acidification. When boiled for a few minutes with formic acid, the solution showed the characteristic ultraviolet spectrum of 9-*t*-butylphenanthrene.

9-t-Butylphenanthrene

Method A.—The carbinol (1 gm.) gave a yellow oil, which was decolorized by chromatography. The partially purified product (0.806 gm.) was transferred to a Späth bulb and maintained at 100–110° at 1–2 mm. for half an hour. A white crystalline sublimate (22 mgm.), m.p. 77–98°, was collected. Crystallization from methanol raised the m.p. to 97–99°, not depressed when mixed with phenanthrene, m.p. 99°. The ultraviolet spectrum of the sublimate was consistent with an 80% phenanthrene content.

The ultraviolet spectrum of the residue was compared with those of standard mixtures of phenanthrene and its 9-*t*-butyl derivative. It showed the presence of a further considerable quantity of phenanthrene together with 9-*t*-butylphenanthrene and a trace of a third component, the latter preventing a reliable analysis being made by this method. The residue was dissolved in methanol, filtered with a little Celite and Norit, and then seeded with 9-*t*-butylphenanthrene (below). When it was left in the ice chest overnight needles (0.4 gm.) separated, m.p. 62–64°, not depressed when mixed with 9-*t*-butylphenanthrene.

Method B gave a colorless oil which rapidly crystallized when scratched with methanol. One crystallization from methanol gave long glistening needles, m.p. 64–65°, (85%). Calc. for $C_{18}H_{18}$: C, 92.26; H, 7.74. Found: C, 92.57; H, 7.77%. The *1,3,5-trinitrobenzene complex* crystallized from methanol as silky, bright yellow needles, m.p. 143°. Calc. for $C_{24}H_{21}O_6N_3$: C, 64.42; H, 4.73; N, 9.39. Found: C, 64.60; H, 5.0; N, 9.17%.

The hydrocarbon was slowly oxidized by iodic acid in boiling acetic acid, giving a small quantity of orange blades (heptane), m.p. 200–203°, not depressed when mixed with phenanthraquinone, m.p. 204°.

Method C was also shown to give 9-*t*-butylphenanthrene.

The carbinol (0.2 gm.) and trichloracetic acid (10 gm.) were heated on the steam bath for 12 hr. The solution then showed the presence of 9-*t*-butylphenanthrene by its ultraviolet spectrum. The product was isolated with chloroform and dissolved in the minimum of methanol containing trinitro-

benzene (0.15 gm.). When this solution was cooled, yellow needles separated, m.p. 139–141°, raised to 142° when mixed with an authentic specimen of the 9-*t*-butylphenanthrene complex.

9-Benzylphenanthrene

9-Benzyl-9-fluorenylmethanol

9-Benzyl-9-fluorenylmethanol was obtained as a colorless oil (84%), a portion of which was left with hexane for several days to induce crystallization. Recrystallization from methanol gave rhombs and irregular six-sided plates, m.p. 97–98.5°. (Reported m.p. 98.5–99.0° (40).) The *tosylate* was prepared in the usual way and crystallized from heptane to give soft blades (94%), m.p. 115°. The melt almost at once recrystallized, this observation prompting the experiments under method *C*. Calc. for $C_{28}H_{24}O_3S$: C, 76.33; H, 5.49. Found: C, 76.23; H, 5.34%.

9-Benzylphenanthrene

Method B: the tosylate was boiled with formic acid, needles starting to separate within a minute. Recrystallization of the product from methanol gave colorless needles (84%), m.p. 155°. (Reported m.p. 156° (40).) *Method C*: the tosylate (0.1 gm.) was melted and the products boiled with water. The insoluble material was collected and crystallized from methanol, giving needles (0.041 gm.), m.p. and mixed m.p. with the sample from method *B*, 155°.

Attempted Preparation of 9-Phenylphenanthrene

9-(α-Hydroxybenzyl)-fluorene

9-Benzoylfluorene (37) (5.17 gm.) was boiled for half an hour with a solution of potassium borohydride (1.5 moles) in methanol–water (80 ml., 2:1). The product was crystallized from carbon tetrachloride, giving prisms (4.1 gm.), m.p. 118–119.5°. (Reported m.p. 118.5–119.0° (21).) Attempts to carry out the reduction in the presence of potassium hydroxide gave a deep yellow solution from which the color was not discharged, even on prolonged boiling.

Treatment of the carbinol with polyphosphoric acid (method *A*) gave a small yield of prisms (hexane), m.p. 70°, which had the ultraviolet spectrum of 9-benzalfluorene (25). (Reported m.p. 76° (32).)

Attempts to prepare the tosylate gave, after crystallization from benzene–hexane, a poor yield of small prisms, melting at 92–95° to a black liquid. Boiling with formic acid produced no significant change in the ultraviolet spectrum, but small prisms of m.p. 122–125° separated on cooling. These experiments were not continued.

Attempted Preparation of Methyl 9-Phenylfluorene-9-carboxylate

A solution of methyl fluorene-9-carboxylate (5 gm.) in dry ether (50 ml.) was added to a well-stirred mixture of liquid ammonia (400 ml.) containing sodamide (from 6 gm., 11 equiv., sodium). After half an hour, bromobenzene (40 ml.) was added to the orange solution which was stirred for four hours more. Ammonia was removed on the steam bath and the residue shaken with

chloroform and water. The product was isolated from the chloroform as an orange oil. When boiled with methanol, this deposited pale buff prisms (*X*) which were collected. The filtrate was concentrated to 10 ml. and left overnight in the ice chest. Next morning, colorless needles (*Y*) were collected. No other crystalline material was obtained, but hydrolysis of the mother liquors with sodium hydroxide in aqueous ethylene glycol gave fluorene (2.9 gm.), m.p. and mixed m.p. 113–114°.

X (0.21 gm.) was insoluble in aqueous potassium hydroxide, did not contain nitrogen, and was sparingly soluble in all the common organic solvents. Attempts to sublime it at 1–2 mm. resulted in complete decomposition. Vigorous hydrolysis gave a yellow gum and a small quantity of a steam-volatile compound, the latter having a fluorene spectrum in the ultraviolet region. The dried prisms melted over a wide range.

Y (45 mgm.) was crystallized from methanol–acetone to the constant m.p. 228°. Calc. for $C_{26}H_{18}$: C, 94.51; H, 5.49. Found: C, 94.55; H, 5.77%. 9,9′-Difluorenyl has m.p. 246–247° (27). The product was very stable, subliming unchanged at one atmosphere.

9-Hydroxymethylenefluorene Tosylate

An aqueous alkaline solution of 9-formylfluorene (10) (equivalent to 0.4 gm. fluorene) was made strongly alkaline and shaken for a few minutes with tosyl chloride (1 gm.). The product was isolated with ether and crystallized from benzene–hexane, giving prismatic needles, m.p. 105–105.5°, (0.2 gm.). Calc. for $C_{21}H_{16}O_3S$: C, 72.39; H, 4.63. Found: C, 72.46; H, 4.58%. The ultraviolet spectrum was unchanged after the needles were boiled in formic acid or ethylene glycol for 12 hr., although some decomposition occurred in the latter solvent.

When the tosylate (0.99 gm.) was hydrogenated over palladium-on-charcoal, 1.1 moles of hydrogen were absorbed in 15 min. The only crystalline material isolated was the unchanged tosylate (0.1 gm.), m.p. and mixed m.p. 104–105°.

9-Fluorenylmethyl Tosylate

The following is typical of many attempts made to prepare this compound: pure 9-fluorenylmethanol (10) (3 gm.) was tosylated in the usual way, using 1.1 moles of tosyl chloride. The dried product was extracted several times with hot heptane and the amorphous residue discarded. Concentration of the extracts and filtration through Magnesol gave, on cooling, small white needles (1.15 gm.), m.p. 145°, not raised by recrystallization from the same solvent. Calc. for $C_{21}H_{18}O_3S$: C, 71.97; H, 5.18. Found: C, 69.87; H, 5.37%.

Crystallization from methanol gave similar results. Found for other samples: C, 65.32, 65.38; H, 4.90, 5.15%.

The tosylate (0.5 gm.) was boiled under reflux with formic acid for 12 hr. Aliquots were withdrawn at intervals and their ultraviolet spectra measured. They showed that phenanthrene was slowly formed, together with a fluorene derivative. Chromatography of the product followed by preparation of the

picrate from benzene gave yellow needles (0.08 gm.). The picrate was decomposed by passage of a hexane solution over a column of activated alumina; evaporation of the eluants and two crystallizations from methanol gave a small quantity of colorless plates, m.p. 95–98°, not depressed when mixed with phenanthrene, m.p. 99°.

The tosyl ester (10.8 mgm.) and anhydrous potassium carbonate (0.2 gm.) were boiled under reflux with dioxane–water (50 ml., 1: 1). Aliquots were withdrawn at intervals and the ultraviolet spectra measured, these showing the gradual appearance of the phenanthrene bands from 330 to 350 mμ which reached a constant intensity after two hours. The presence of a fluorene derivative prevented an analysis being made.

The ultraviolet spectrum of a solution of 9-fluorenylmethanol in formic acid was unchanged after prolonged boiling, with or without the addition of sulphuric acid.

Methyl 9-Bromofluorene-9-carboxylate

Treatment of methyl fluorene-9-carboxylate (1 gm.) in chloroform (10 ml.) with bromine (0.75 gm.) and four subsequent crystallizations from heptane gave needles, m.p. 121–130°, probably containing nuclear bromine.

The ester (1 gm.) and fused sodium acetate (1 gm.) were dissolved in acetic acid (15 ml.) and bromine (0.75 gm.) added. Next morning, the product was isolated with carbon tetrachloride and crystallized from hexane, giving pale yellow prisms (0.6 gm.), m.p. 106–107°. (Reported m.p. 108.5–109.0° (22).) A methanolic solution gave an instantaneous precipitate of silver bromide when treated with silver nitrate.

Experiments with Benzilic Acid

(i) A mixture of polyphosphoric acid (200 ml.) and benzilic acid (4 gm.) was stirred at 160–180° for two hours. Long slender needles (0.2 gm.) sublimed onto the sides of the vessel and were identified as fluorene-9-carboxylic acid, m.p. 226–228°; decarboxylated over copper bronze to fluorene, m.p. and mixed m.p. 114°. The mother liquors yielded benzilic acid when worked up in the usual way.

(ii) Benzilic acid (5 gm.) was tosylated in the usual way with tosyl chloride (1.1 moles) in pyridine. Crystallization of the product from benzene–hexane gave prisms (4.6 gm.), m.p. 195°, identified as benzilide. (Reported m.p. 196° (1, 23).) Attempts to tosylate methyl benzilate gave back the ester unchanged.

(iii) Treatment of benzilic acid or methyl benzilate with anhydrous hydrogen fluoride did not give detectable amounts of fluorene derivatives.

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THE RELATIVE REACTIVITIES OF 1,2-*trans*-SUGAR ACETATES[1]

By R. U. Lemieux and Carol Brice

ABSTRACT

The rates of exchange of the C1-acetoxy group of a variety of 1,2-*trans*-sugar acetates with acetate from stannic trichloride acetate labelled with carbon-14 were determined in chloroform containing stannic chloride. A correlation was found to exist between reactivity and configuration with the configuration at C3 playing a dominating role. The greater reactivity of the 2,3-*trans*-sugar compounds is attributed to steric inhibition to the formation of the resonance stabilized intermediate 1,2-cyclic carboxonium ion in the case of the 2,3-*cis*-compounds.

In view of the central role played by acetylated sugars, glycosides, and glycosyl halides in the field of synthetic carbohydrate chemistry, it is important that the chemical properties of these substances be well understood. It is especially important that information be gained on those factors which affect the reactivity of the C1 to aglycon group bond. Such data are not, however, readily obtained. The unstable anomers of most of the acetylated glycosyl halides are not suitable for study because of their extremely high reactivity (14, 22). On the other hand, the much more inert acetylated alkyl glycosides possess the undesirable property of undergoing reaction by way of very complex reaction routes (19). Both the anomeric forms of sugar acetates are usually sufficiently unreactive to allow purification and the results of studies on pentaacetates of glucose (15), galactose (14), and mannose (16) suggest that these substances undergo reaction at the anomeric center in a reasonably straightforward fashion. The sugar acetates therefore appeared more attractive for study than the closely related acetylated glycosides and glycosyl halides. In view of the evidence (14, 16, 18) that 1,2-*trans*-sugar acetates tend to undergo reaction at the anomeric center with participation of the C2-acetoxy group, it appeared desirable to consider these compounds as a group. The behavior of the compounds could of course be studied under a wide variety of reaction conditions. It appeared to us that perhaps the reaction conditions least susceptible to complicating factors would be those developed by the authors (16) in which the rate of exchange—concurrent with anomerization—of acetate between the C1-acetoxy group of a sugar acetate and stannic trichloride acetate (labelled in the carboxyl group with carbon-14) is determined. The exchange technique (16) was applied to the four diastereoisomeric 1,2-*trans*-aldopentopyranose tetraacetates, five diastereoisomeric 1,2-*trans*-aldohexopyranose pentaacetates (glucose, mannose, galactose, altrose, and allose), and the 1,2-*trans*-acetates of 6-deoxyglucopyranose and D-glycero-D-guloheptopyranose. Data typical of the experimental results are plotted in Figs. 1, 2, 3, and 4.

A consideration of the data shows that the reaction followed the simple exponential law for exchange reactions (4) during the early stages. However,

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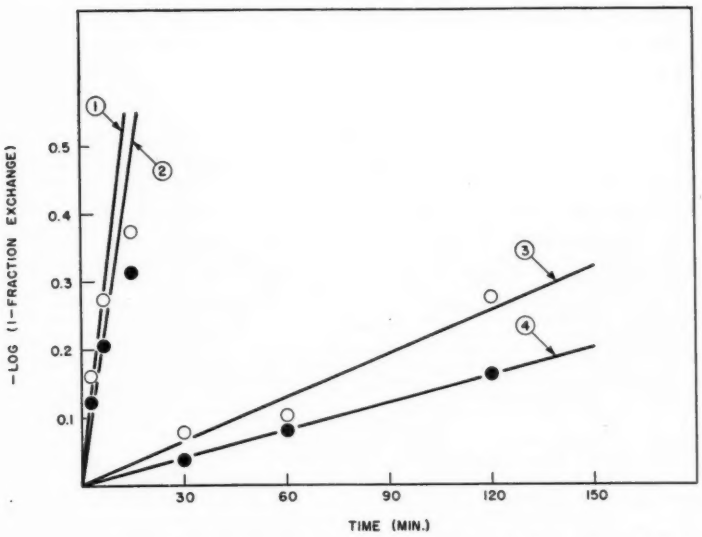


FIG. 1. Rates of exchange under the conditions given in Table I at 20° C.
Plot 1. β-D-xylopyranose tetraacetate—○
Plot 2. α-L-arabinopyranose tetraacetate—●
Plot 3. β-D-ribopyranose tetraacetate—○
Plot 4. α-D-lyxopyranose tetraacetate—●

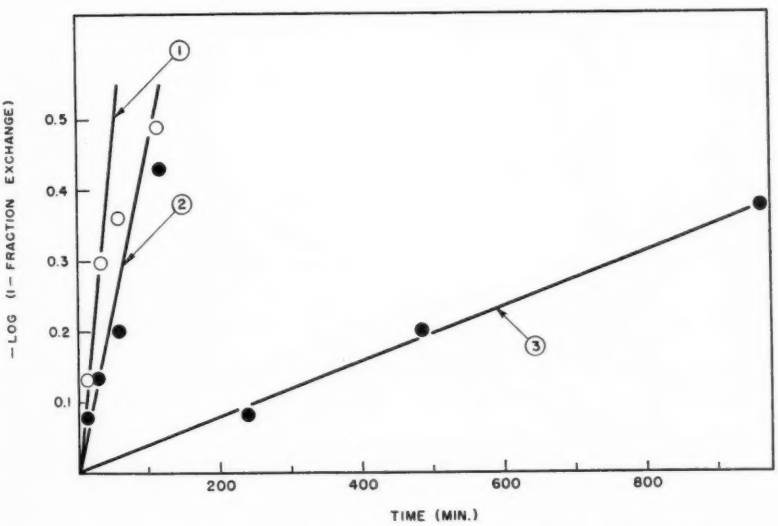


FIG. 2. Rates of exchange under the conditions given in Table I at 20° C.
Plot 1. α-D-altropyranose pentaacetate—○
Plot 2. β-D-glucopyranose pentaacetate—●
Plot 3. α-D-mannopyranose pentaacetate—●

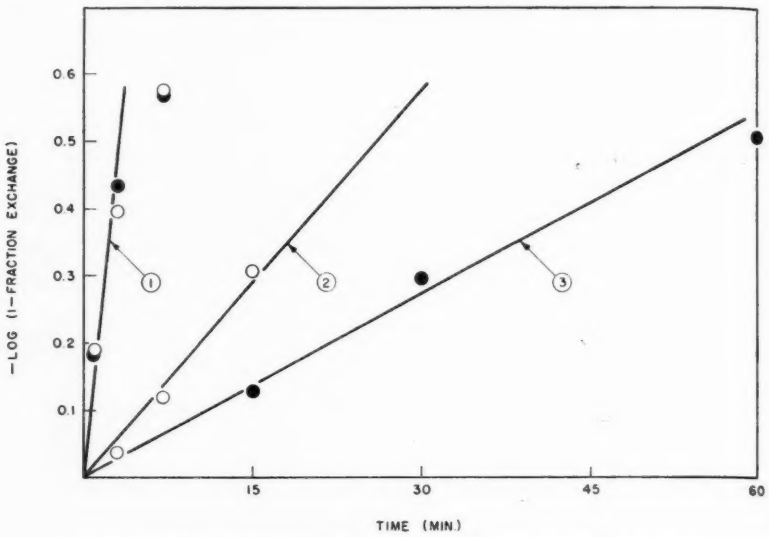


FIG. 3. Rates of exchange under the conditions given in Table I at 40° C.
Plot 1. β-D-xylopyranose tetraacetate—○ and
α-L-arabinopyranose tetraacetate—●
Plot 2. β-D-ribopyranose tetraacetate—○
Plot 3. α-D-lyxopyranose tetraacetate—●

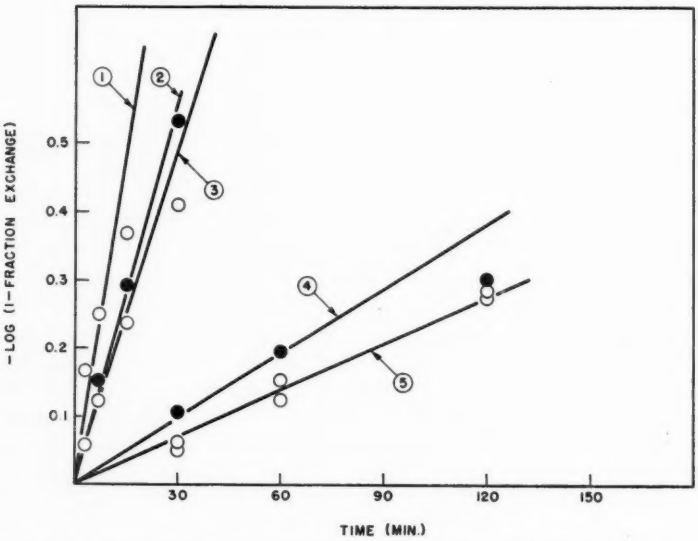


FIG. 4. Rates of exchange under the conditions given in Table I at 40° C.
Plot 1. α-D-altropyranose pentaacetate—○
Plot 2. β-D-glucopyranose pentaacetate—●
Plot 3. β-D-galactopyranose pentaacetate—○
Plot 4. β-D-allopyranose pentaacetate—●
Plot 5. α-D-mannopyranose pentaacetate—○

it is seen that in several cases there was strong deviation after about 60% exchange. This is the situation to be expected under conditions where the exchange reaction is accompanied by a reaction which leads to replacement of the C1-acetoxy group. Pacsu (21) has shown that the reaction of a sugar acetate with stannic chloride can yield acetochlorosugar and, in fact, in the present experiments the reaction products isolated after the prolonged reaction times invariably contained chlorine. However, the results indicate clearly that in all cases the formation of acetochlorosugar was much slower than the exchange. Consequently, it can be assumed that the slope of the line (log(1−fraction exchange) versus time) drawn through the points obtained in the early stages of the reaction is proportional to the rate of exchange and can serve as a measure of the reactivity of the sugar acetate under the conditions used. Since the initial conditions were the same for each sugar acetate, a comparison of the slopes provides a measure of the relative reactivities of the sugar acetates. The relative reactivities listed in Table I were calculated setting the

TABLE I

RELATIVE RATES OF EXCHANGE OF ACETATE BETWEEN 1,2-*trans*-SUGAR ACETATES AND STANNIC TRICHLORIDE ACETATE

The sugar acetate, 1 mM., was dissolved at zero time in 20 ml. of chloroform containing 1 mM. of stannic chloride and 1 mM. of stannic trichloride acetate labelled in the carboxyl group with carbon-14 (16)

Fully acetylated pyranose form	Temperature of reaction: 20° C. Relative rates Found	20° C. Calc.[a]	40° C. Relative rates Found	40° C. Calc.[b]	Temperature coefficient, $R_{40°}/R_{20°}$
β-D-Xylose	100[c]	100	100[c]	102	4.0
α-L-Arabinose	81	96	100	95	4.9
β-D-Ribose	5.3	7	11.9	13	9.0
α-D-Lyxose	3.3	3	5.7	6	7.0
α-D-Altrose	23	32	21	19	3.6
β-D-Glucose	11.8	12.5	11.9	12.8	4.0
β-D-Galactose	8.7	12	10.6	12	4.9
β-D-Allose	—	—	2.00	1.6	—
α-D-Mannose	0.98	1.0	1.43	1.2	5.9
β-D-6-Deoxyglucose	—	—	7.8	—	—
D-Glycero-β-D-guloheptose	0.032	—	—	—	—

[a] *Using equation [1].*
[b] *Using equation [2].*
[c] *Arbitrarily set at 100.*

reactivity of β-D-xylopyranose tetraacetate at 100 for both the runs made at 20° C. and at 40° C. The increase in reactivity caused by the increase in temperature is shown.

No difficulty was experienced in reproducing the values listed in Table I within the limits of the rather large experimental error. This is seen, for example, by the plots in Fig. 4 of two runs for α-D-mannopyranose pentaacetate. To ensure against any difficulties in reproduction which are often reported for reactions catalyzed by Lewis acids such as stannic chloride, several of the sugar acetates were always run together using the same stock solution of stannic chloride and stannic trichloride acetate. Furthermore, a

sugar acetate was used as a control by including it in each batch of runs. The reactivity of the compound used as control never varied significantly from one run to the next.

The results allow broad conclusions on the effect of configuration on the reactivity of a 1,2-*trans*-sugar acetate which are in no way obscured by the uncertainties in the experimental data. Examination of the content of Table II

TABLE II

THE EFFECT OF CONFIGURATION ON THE REACTIVITY OF A 1,2-*trans*-SUGAR ACETATE

	Ratio of reactivities[a]	
	20° C.	40° C.
1. 1,3-*cis*-Compound/1,3-*trans*-Epimer		
(*a*) xylo/ribo	19	8
(*b*) arabo/lyxo	25	18
(*c*) gluco/allo	—	6
(*d*) altro/manno	25	15
2. 1,4-*trans*-Compound/1,4-*cis*-Epimer		
(*a*) xylo/arabo	1.2	1.0
(*b*) ribo/lyxo	1.6	2.1
(*c*) gluco/galacto	1.4	1.1
3. 1,5-*trans*-Compound/1,5-*cis*-Epimer		
(*a*) altro/galacto	2.6	2.0
4. Introduction of CH_2OAc at C5 of a pentose acetate in *cis*-relationship to the C1-acetoxy group		
(*a*) xylo/gluco	8.5	8.4
(*b*) ribo/allo	—	6.0
(*c*) arabo/galacto	9.3	9.4
5. Introduction of CH_2OAc at C5 of a pentose acetate in *trans*-relationship to the C1-acetoxy group		
(*a*) arabo/altro	3.5	4.8
(*b*) lyxo/manno	3.4	4.0

[a]*The reactivities are listed in Table I.*

shows that epimeric 1,2-*trans*-sugar acetates differ greatly in reactivity when the difference in configuration is at C3. In fact, it seems clear that for a group of diastereoisomeric 1,2-*trans*-sugar acetates, the configuration at C3 has the overriding influence on reactivity. The data indicate that the compounds differ little in reactivity when the epimerism is at C4. It is seen that a pentose acetate is considerably more reactive than the homomorphous hexose acetate, the introduction of a CH_2OAc group for hydrogen at C5 of a pentose causing an about eight-fold decrease in reactivity when introduced *cis* to the C1-acetoxy group and an about four-fold decrease when introduced in *trans*-relationship.

Before considering these matters in detail, it is of interest to note that it is possible to correlate within an impressive degree of accuracy the reactivities at a given temperature listed in Table I by means of simple mathematical expressions ([1] and [2]). These expressions were derived empirically by giving the symbols a, b, c, x, y, and z in formula I values of zero when they correspond to a hydrogen atom and values of one when they correspond to an acetoxy or

CH_2OAc group and arriving at their coefficients by trial and error. The calculated reactivities at 20° C. listed in Table I were calculated from the expression

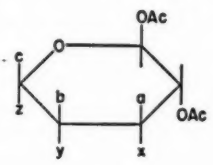
$$[1] \qquad R_{20^\circ} = \frac{95a+2x+b+5y}{7c+2z+1},$$

and the expression

$$[2] \qquad R_{40^\circ} = \frac{94a+5x+b+8y}{7c+4z+1}$$

was used at 40° C. It seems reasonable that these correlations between reactivity and configuration should exist since steric effects can be expected to play the dominating role in determining the *relative* reactivities of closely related diastereoisomeric compounds and the steric effects are determined by configuration.

Several attempts have been made recently (5, 6, 11) to correlate the reactivities of sugar derivatives in reactions at the anomeric center with the stabilities of the compounds as judged by conformational analysis. The present results have an important bearing on these speculations. It seems well established (16, 17) that the dissociation of the C1-acetoxy group of a 1,2-



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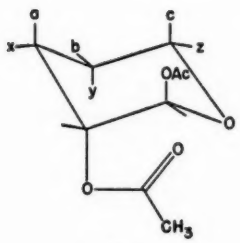

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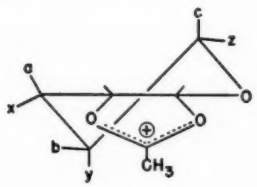


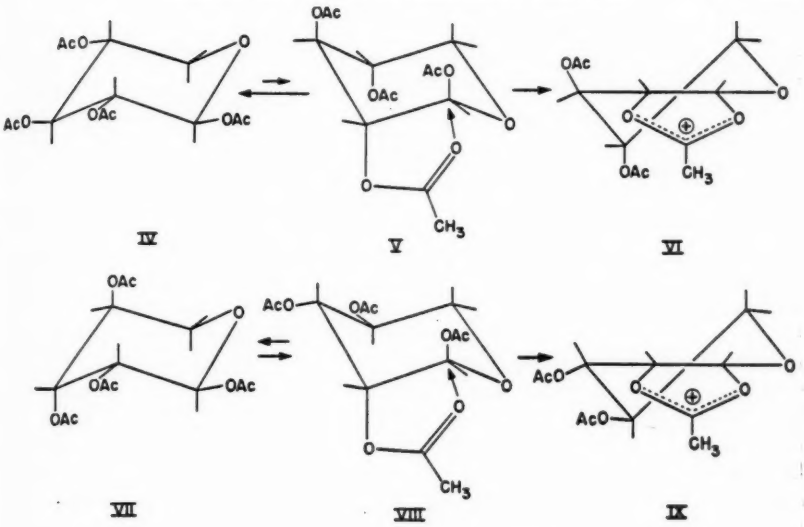
III

trans-sugar acetate proceeds primarily with *direct* participation of the C2-acetoxy group. Therefore, it can be expected that these compounds achieve the conformation of II before dissociation can begin since axial orientations for the leaving and participating groups should be the most favorable situation (24). Direct evidence has been obtained that this is the case in the dissociation of 1,2,3,4-tetra-*O*-acetyl-β-D-glucose by stannic chloride (15). Obviously, on the basis of these considerations one would not expect β-xylose tetraacetate to be the most reactive 1,2-*trans*-pentose tetraacetate if only the ground states of

the molecules are considered since β-xylose tetraacetate in conformation II possesses all four acetoxy groups in axial orientations. The high reactivity of this compound can however be rationalized by a conformational analysis of the steric requirements for the formation of the intermediate 1,2-cyclic carboxonium ion III. The basis for depicting the ion in the particular conformation shown has been discussed by Lemieux and Cipera (18). The steric requirements for the ion III can be met, of course, with the pyranose ring in a boat conformation and it is noteworthy that a superficial rationalization of the present data can be based on the boat form which would possess the five-membered ring in "equatorial" orientation. However, this must be merely a coincidence since the direct formation of III in this conformation appears unlikely for a number of reasons which will become clearly apparent in the foregoing discussions.

Winstein and co-workers (23) have shown that the driving force for reaction provided by neighboring acetoxy group participation is related mainly to the heat of activation term in the transition-state-theory expression for specific rate of reaction and this result was related to resonance stabilization of the 1,2-cyclic-carboxonium-ion intermediate. The fact that any instability or stability factor in the intermediate ion is in all probability present to an important extent in the transition state is basic to these discussions.

Definite evidence has accumulated (16, 18) that, as expected from the work of Winstein and co-workers (23), the participation of the C2-acetoxy group in the dissociation of a 1,2-*trans*-sugar acetate can provide a powerful driving force for the reaction. The present results indicate that in all probability the strong influence of the configuration at C3 on the reactivity of these substances is mainly related to steric inhibition to achievement and to resonance stabilization of the ion by deformation of the planar five-membered ring structure when the C3-acetoxy group is in *cis*-relationship to the C2-substituent because of eclipsing of these groups in the half-chair conformation of III. The basis for this conclusion is readily seen from a consideration of the data for the pentose acetates. Although the results listed in Table I are subject to rather large experimental error, there can be no doubt that the reactions of the 2,3-*cis*-pentose acetates possess much higher temperature coefficients than do those of the 2,3-*trans*-diastereoisomers (Formulas IV–IX). In the case of the xylose (IV–V) and lyxose (VII–VIII) derivatives these coefficients correspond to energies of activations of roughly 13 and 18 kcal. per mole, respectively. Therefore, the heat of activation for the xylose derivative is about 5 kcal./mole less than for the lyxose compound. This observation is in accord with the above postulation that the higher reactivity of the xylose tetraacetate (IV–V) is related to steric inhibition to achievement of resonance stabilization in the ion (IX) derived from the lyxose compound (VII–VIII). Since Winstein and co-workers (23) have concluded that neighboring acetoxy group participation can lend a driving force for reaction of this order (4.6 kcal./mole at 25° C.), the results suggest strong steric inhibition to resonance in the ion IX. It will be seen below that the configuration at C4 in the ion IX also contributed to this condition.



Since a difference in heat of activation of 5 kcal./mole would require a difference in reactivity by a factor of about 3000 and the xylose compound is only 30 times more reactive than the lyxose tetraacetate, it is evident that the entropy of activation for the former compound must be much greater (about nine entropy units) than the latter substance. This situation appears reasonable from a consideration of the substances in their ground states relative to the transition states. Since the xylose tetraacetate must exist almost entirely in the conformation IV while the structure VIII is highly probable for the lyxose tetraacetate, it follows that the lyxose derivative exists in a conformation which is much closer to that of the transition state than does the xylose compound. Therefore, it is reasonable that the probability for achievement of the transition state (entropy of activation) should be greater for the lyxose tetraacetate than for the xylose diastereoisomer.

The fact that the configuration at C3 plays a dominating role among the factors which determine the reactivity of 1,2-*trans*-sugar acetates therefore appears related to the more ready achievement and more effective resonance stabilization of the intermediate carboxonium ion (III) in the case of the 2,3-*trans*-compounds. Thus, the large coefficients for a in expressions [1] and [2] are understandable. This conclusion promises to be of practical value since it appears to provide a deepened understanding of the properties of related compounds. For example, the fact that β-D-xylopyranosyl chloride triacetate (22) appears to be more reactive than β-D-ribopyranosyl chloride triacetate (25) is no longer surprising. Lemieux and Cipera (18) have shown that the hydrolysis of an acetylated sugar (methyl 1,2-orthoacetate) catalyzed by acid in all probability proceeds by way of the 1,2-cyclic carboxonium ion (III). Therefore, the fact that 2,3-*cis*-mannose (methyl 1,2-orthoacetate) triacetate is more resistant to hydrolysis than the corresponding 2,3-*trans*-derivative of glucose

(14) appears at least in part understandable. Also, Isbell and Frush (13) have found the course of the reaction of 2,3-*cis*-α-D-mannopyranosyl bromide tetraacetate with methanol in the presence of silver carbonate to be markedly temperature dependent and to yield substantial amounts of methyl β-D-mannopyranoside tetraacetate. This result clearly points to a steric hindrance to reaction with participation of the C2-acetoxy group which is increased by increased kinetic disturbance of the molecule.

The deactivation which results on the introduction of a CH_2OAc group for a hydrogen atom at C5 of a pentose acetate is reminiscent of the same result found in the hydrolysis of methyl glycopyranosides (12). The present discovery that the configuration of C5 in the case of the hexose acetates has only a twofold to threefold effect on reactivity was unexpected in view of the important role the CH_2OAc group has been predicted to play in determining the reactivity of related compounds (9). The fact that deactivation occurs for both the configurations of C5 could be taken as indication that the effect is mainly electronic in nature. However, we submit that the deactivations are produced mainly by steric factors. The deactivation brought about by a large substituent at *c* can be attributed to the instability of conformation II and to the interference by this substituent when in axial orientation with the coordination of the acid catalyst with the C1-acetoxy group. The deactivation caused by an increase in the bulk of the substituent at *z* can, on the other hand, be attributed to steric inhibition to achievement of the half-chair conformation (III) for the carboxonium ion, which results from the fact that in the conformation of III, the *z* and *b* substituents are very nearly in one plane. Angyal and Macdonald (1) have provided chemical evidence for the eclipsing of these *trans*-substituents in the half-chair conformation and this fact is clearly demonstrated by a molecular model (3). Furthermore, this view is supported by the surprising observation that the preferred configuration at C4 for reactivity is that which possesses the large substituent in axial orientation (*y*) both in II and III since this odd result can only be rationalized through the assumption that eclipsing of the substituents at *b* and *z* renders the half-chair conformation (III) unstable. It is to be noted in this respect that substituents at *y* and *c* introduce much less instability in the half-chair conformation (III) than in the chair form (II) since in III there are no opposing axial groups.

The above conclusions appear to be of practical use. This fact is illustrated by the following considerations. First of all, for D-glycero-β-D-guloheptopyranose hexaacetate to undergo dissociation of the C1-substituent with participation of the C2-acetoxy group, the large $-CHOAcCH_2OAc$ group must achieve axial orientation (*c*) and the C3-acetoxy group (*x*) must eclipse the 1,2-ring structure in the ion III. Thus, the relatively great unreactivity found for this substance is not surprising. Furthermore, the fact (10) that 1,2-*trans*-D-glycero-β-D-guloheptopyranosyl chloride pentaacetate reacts with inversion of the anomeric center to form acetylated methyl α-D-glycoside *in quantitative yield* under conditions which normally afford a 1,2-orthoacetate appears understandable at least to the extent that it is not surprising that the compound should react by way of a route other than the highly sterically hindered

route involving C2-acetoxy group participation. It has been reported (7) that 1,2-*trans*-D-glycero-α-D-idoheptopyranosyl bromide reacts with extensive inversion of the anomeric center when treated with methanol and silver carbonate. It is not surprising that the reaction should tend not to involve participation of the C2-acetoxy group when it is realized that achievement of the ion III involves bringing the C4-acetoxy group and the large $-CHOAcCH_2OAc$ group into nearly eclipsed orientations.

In conclusion, it can be stated that work along the lines reported in this communication promises to yield a much deepened insight into the properties of certain sugar derivatives. Although the present results allow certain important conclusions, the rather large uncertainties in the experimental results do not allow as detailed a theoretical analysis as would be desirable. It is hoped that improved conditions for studying the relative reactivities of sugar acetates will be discovered. The method used by Lemieux, Brice, and Huber (17) promises to yield superior experimental data. Perhaps the most important contribution of the present work is the clear illustration of the dangers attendant in any attempt to rationalize reactivities through the consideration of the relative stabilities of the substances in their ground states while disregarding structures and stabilities of the transition states.

ACKNOWLEDGMENTS

The authors wish to express sincere thanks to Dr. A. C. Neish for the generous gift of the rare sugars and to Dr. Ludovic Ouellet for useful discussions.

EXPERIMENTAL

Except for the β-D-allose pentaacetate, the compounds were prepared by published methods (2, 8) and recrystallized to a high state of purity.

D-Allose, 1 gm., was heated on the steam bath for two hours with 1 gm. of sodium acetate and 15 ml. of acetic anhydride. The sirupy product, 1.90 gm., $[\alpha]_D$ −3.28° (chloroform) was isolated in the usual manner. Chromatography on Magnesol-Celite according to the procedure of McNeely, Binkley, and Wolfrom (20) readily afforded 0.61 gm. of crude crystalline material which was purified by recrystallization from ethanol. The compound, m.p. 97–100° C., $[\alpha]_D$ −14.6° (*c* 1.5, in chloroform), was assumed to possess the β-D-configuration on the basis of its rotation and the stable pyranose structure on the basis of the yield.

The technique used to determine the rates of exchange has already been reported in detail by Lemieux and Brice (16).

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NOTES

A LOW TEMPERATURE CELL FOR USE WITH THE CARY ULTRAVIOLET SPECTROPHOTOMETER[1]

By R. N. Jones and D. S. Keir

Several cells have been described for the measurement of ultraviolet absorption spectra at low temperatures (7, 11, 1, 8, 9, 4, 6). Most of these have been designed to handle samples cooled to rigid glasses at liquid nitrogen temperature, following the technique developed by Lewis and Lipkin (5). The cell to be described here is suitable for use with liquids at all temperatures down to −196°C. using liquid nitrogen as coolant. The essential feature is the design of the low temperature section as a single unit of fused quartz; this eliminates the strain problems that arise when adhesive seals are cooled or warmed too rapidly.

CONSTRUCTION OF THE CELL

The apparatus is shown diagrammatically in Fig. 1. It consists of a double walled inner cell (*A*) (4.3 cm. long × 0.9 cm. diameter), which is made of quartz with fused-on end windows. This is surrounded by an outer jacket (*B*) of Pyrex glass with quartz windows (*C*, C_1) attached with Benelite cement. The outer jacket can be evacuated through the stopcock (*D*). Simple evacuation provides sufficient thermal insulation to prevent frosting of the windows, so that silvering of the walls is unnecessary. This simplifies the observation of the inner cell during the cooling and measuring process. Access to the inner cell is provided through the narrow glass filling tube (*E*), which is attached to the quartz cell through a graded seal. The temperature in the cell is recorded by a fine thermocouple (not shown in the diagram) which passes down through (*E*). This thermocouple can be withdrawn immediately before the spectrum is measured, or it can be left in the beam and its obscuration allowed for in the solvent control measurement.

The cell is cooled through the quartz annular jacket (*F*), which is fused to it and extends from one end to a point 4 mm. from the opposite end, allowing clearance for the filling tube (*E*). The annular space is open to the center of the apparatus, to which it is attached through a graded seal that provides the main support. The annular space is filled with fine copper shot to increase the thermal capacity. The cell is demountable for cleaning and repair at the 50/60 standard ground joint which forms the upper part of the outer jacket. To cool the cell liquid nitrogen is dropped down the center of the apparatus at *G* from the reservoir. This is a Dewar flask provided with a glass needle valve (*H*) controlled by a screw passing down from the top.

[1]*Issued as N.R.C. No. 3964.*

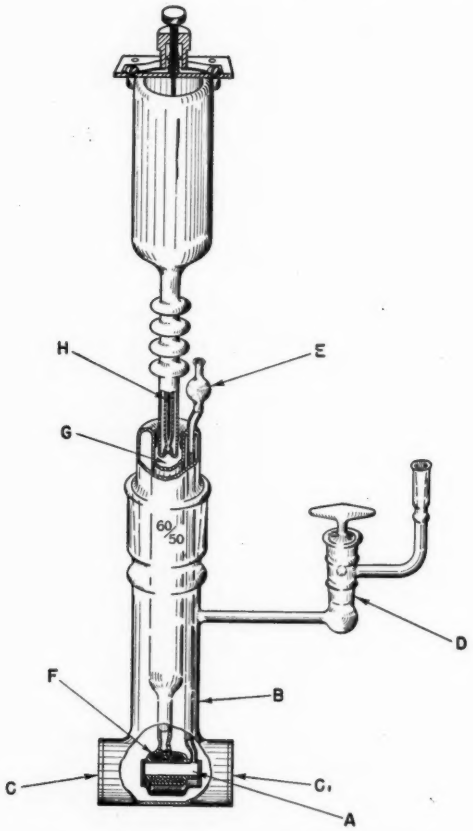

FIG. 1. Constructional details of the cell.

OPERATION

The apparatus is aligned in the upper cell compartment of the Cary spectrophotometer (sample beam) and two 1 cm. quartz cells of conventional type are placed in series in the lower compartment (reference beam). One of these cells is empty, to compensate for reflection losses at the outer quartz windows. In initial experiments the second cell was filled with the solvent used in the experimental cell, but later it was found more convenient to keep this cell filled with distilled water.

Before the experimental solution is measured, a control curve is first obtained. The cell is filled to the top of the filling tube (*E*) with the solvent, the thermocouple leads inserted, and liquid nitrogen dropped into the cooling chamber at a rate of about one drop per second until the temperature reads −80°C. The nitrogen flow is then reduced so that the temperature first levels off near −110°C. and then increases slowly to −100°C. The cell is held at

this temperature for 10–15 min. after which the solvent control spectrum is recorded. The spectrophotometer is housed in a room that can be darkened; the cell compartment is covered with a black cloth, and the actual measurement made with the room lights out and localized red illumination on the strip-chart recorder.

Provided the solvents are pure, these control curves show a steadily increasing absorption from about 0.1 optical density units at 4000 Å to 0.5 optical density units at 2300 Å; no measurements have been attempted at shorter wavelengths.

The cell is next allowed to warm to room temperature, this procedure being accelerated, if necessary, by opening the vacuum in the outer jacket. The solvent is replaced by the absorbing solution and the process repeated. To assure establishment of thermal equilibrium in the cell the spectrum can be rescanned several times until no further change is noted.

The molecular extinction coefficient corrected to room temperature (E_λ) is calculated from the equation

$$E_\lambda = \frac{1}{c.l} \cdot \frac{d_{22}}{d_{-100}} (OD_{soln} - OD_{solv}),$$

where c is the concentration of solute in moles per liter at room temperature (22°C.); d_{22} and d_{-100} the specific gravities of the solvent at 22° and −100°C. respectively; l the cell length in centimeters, which is determined optically from measurements of the absorption of standard potassium chromate solution (2); OD_{soln} the optical density of the solution as measured above, and OD_{solv} the correction term obtained from the solvent control measurement.

This cell has been used for solutions in ethanol, *n*-pentane, and isopentane. In the case of ethanol, care is needed to avoid excessive cooling, as on two occasions the cell has been fractured by solidification of the solvent. Hydrocarbon solvents were prepared by chromatographic adsorption on silica gel in a closed system protected from atmospheric moisture. Repeated experiments in which the same solutions were recooled showed variations in the optical density measurements in a range of ±0.05 *OD* units. These are larger than the variations reported by Potts (9) and by McConnell and Tunnicliff (6) in their measurements on glasses, but they are adequate for the purposes for which the cell was designed (10).

RESULTS

The spectra of naphthalene and anthracene obtained at room temperature and at −100° in ethanol solution with this cell are shown in Figs. 2 and 3. Other examples of the spectra of 1,2-benzanthracene derivatives in *n*-pentane solution will be published elsewhere (3, 10).

ACKNOWLEDGMENT

We are very grateful to Mr. G. Ensell for valuable assistance in the design and construction of this cell.

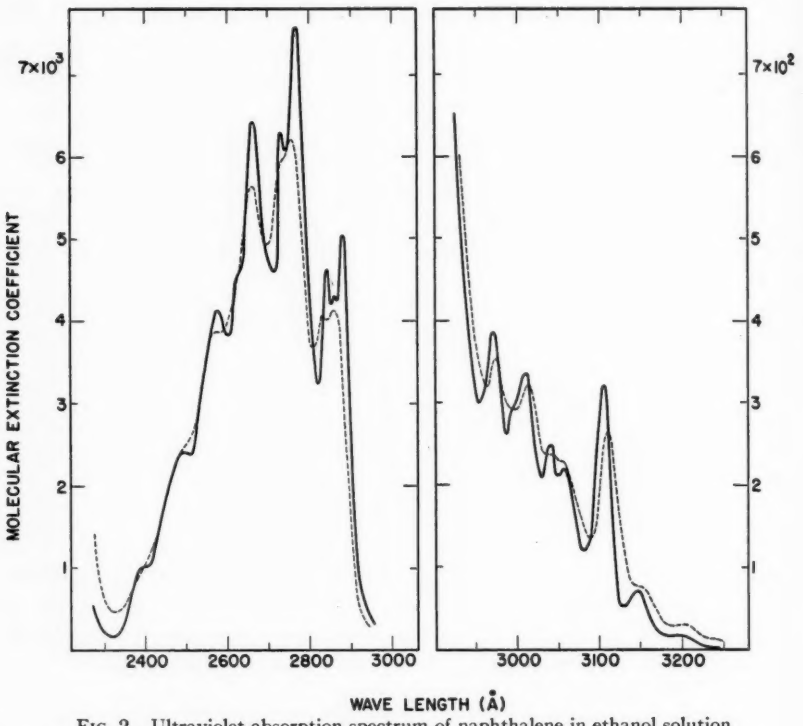

FIG. 2. Ultraviolet absorption spectrum of naphthalene in ethanol solution.
------ At 20°C. ——— At −100°C.

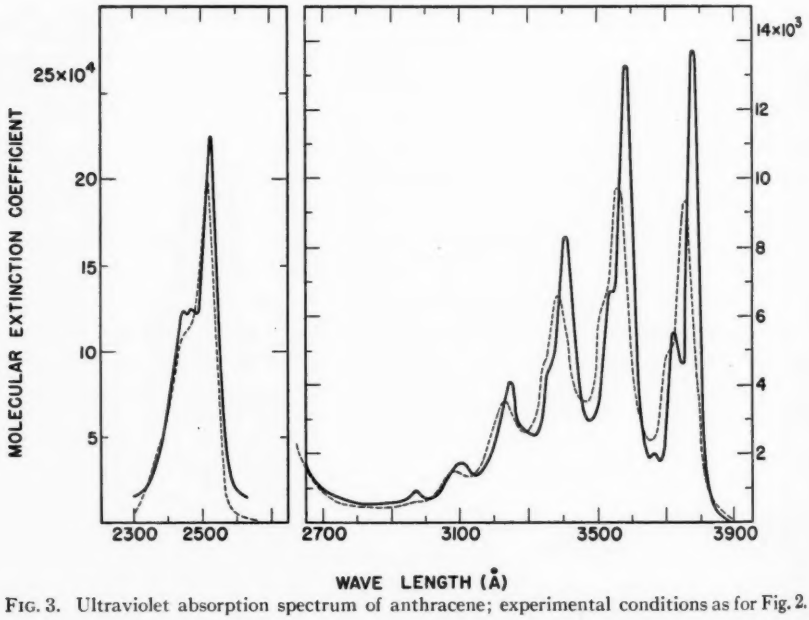

FIG. 3. Ultraviolet absorption spectrum of anthracene; experimental conditions as for Fig. 2.

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PHOTOLYSIS OF KETENE IN THE PRESENCE OF HYDROGEN

BY J. CHANMUGAM* AND MILTON BURTON

In a recent paper (3) on the photolysis of ketene in the presence of hydrogen, Gesser and Steacie† conclude that their results are such as to indicate that the reaction (1, 4)

$$CH_2 + H_2 \rightarrow CH_4 \qquad [3a]‡$$

occurs with low yield at room temperature and is unimportant at higher temperature, and that the reaction

$$2CH_3 \rightarrow C_2H_6 \qquad [5]$$

is the principal source of ethane.

The paper (2) to which Gesser and Steacie refer includes results on the photolysis of ketene in the presence of deuterium, of mixtures of hydrogen and deuterium, of acetone, and of CD_4, all as a function of temperature in the range 27° to 412°. Since the data are given in the form of extensive tables, some of the implications are not obviously apparent. One of the most important implications concerns the probability of ethane formation in ketene photolysis *via* reactions such as [5] in the presence of hydrogen or deuterium.

Fig. 1 summarizes the data for ethane yields from the photolysis of pure ketene and from the photolysis of ketene in the presence of deuterium or of an equimolar mixture of hydrogen and deuterium. The presence of hydrogen and deuterium causes a substantial increase in the yield of C_2H_6 and gives also $C_2H_4D_2$. In the presence of deuterium alone, $C_2H_4D_2$ but no C_2H_6 is produced. Significantly, no C_2H_5D is found. Our ability to recognize the "odd" mixed ethanes, if present, by the mass-spectrometric techniques employed is shown by our experiments (*not* included in Fig. 1) on the photolysis of ketene in the presence of CD_4. In the latter experiments, only C_2H_6, $C_2H_4D_2$, and $C_2H_2D_4$

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†We are indebted to Drs. Steacie and Gesser for the opportunity to see this paper prior to publication.

‡Equation numbers are those of Gesser and Steacie.

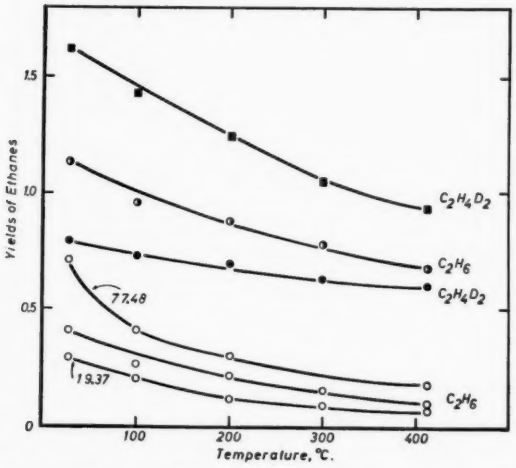

FIG. 1. Ethane yields in the photolysis of ketene, pure and in mixtures (2).
Initial concentrations are in units of 10^{-7} moles ml.$^{-1}$
Yields are in units of 10^{-8} moles ml.$^{-1}$
Initial concentrations: Ketene 38.74 unless otherwise indicated.
○: Pure ketene.
●◑: Mixture of H_2 and D_2, each 19.37.
■: D_2 38.74.

are found at room temperature but the odd mixed ethanes C_2H_5D, $C_2H_3D_3$, and C_2HD_5 (as well as C_2D_6) appear at the higher temperatures.

If C_2H_6 in our work with hydrogen and deuterium were produced by reaction [5], as postulated by Gesser and Steacie for their work with hydrogen, we should have expected also that the reactions

$$CH_2 + H_2 \rightarrow CH_3 + H, \qquad [3]$$

$$CH_2 + D_2 \rightarrow CH_2D + D \qquad [3']$$

might likewise yield ethane by the reaction

$$CH_3 + CH_2D \rightarrow C_2H_5D. \qquad [5']$$

The absence of C_2H_5D in our work has led us to the conclusion that ethane produced in the photolysis of ketene in the presence of hydrogen cannot to any significant degree result from a reaction such as [5].

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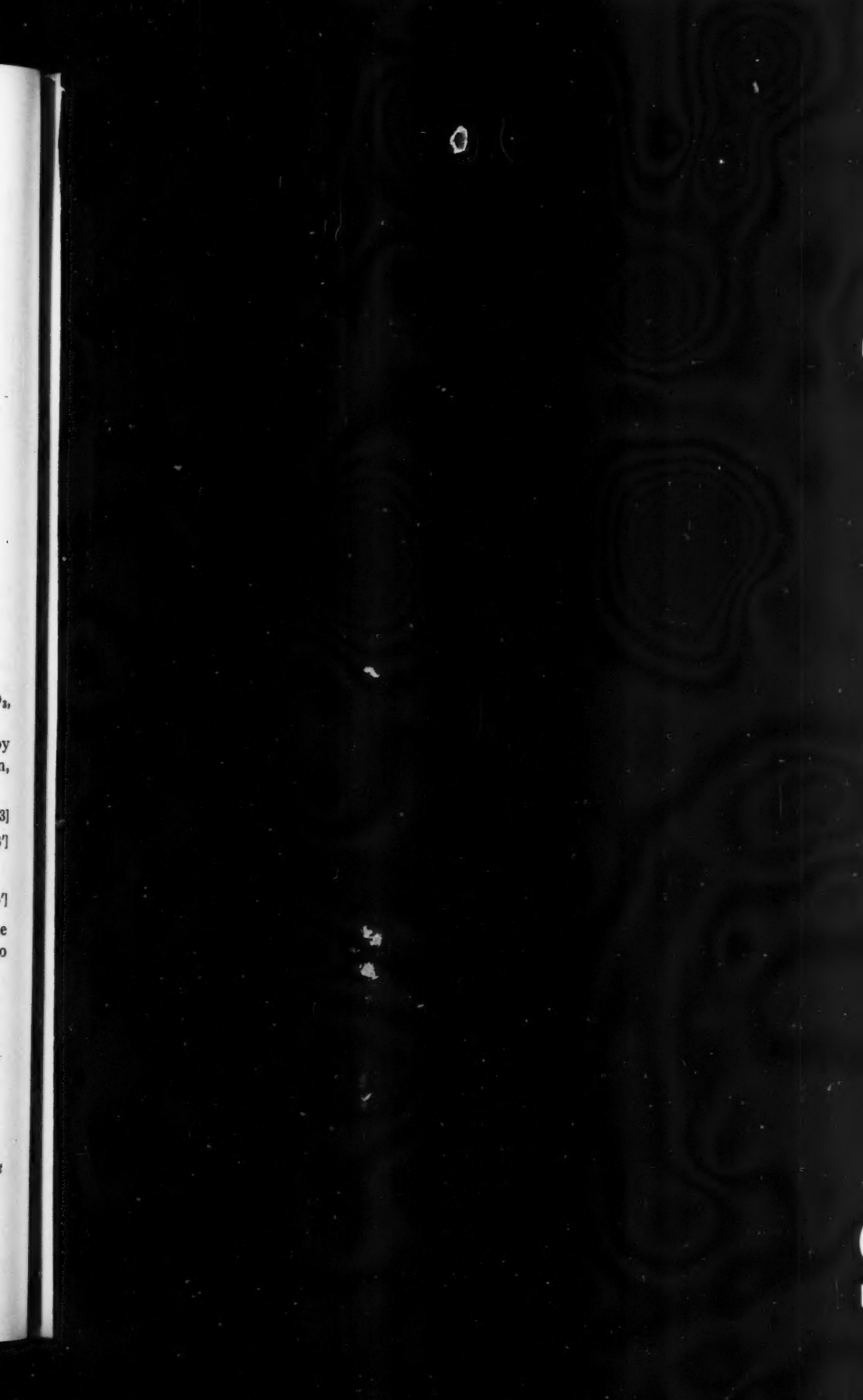

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